Field testing of fiber-optic distributed acoustic sensing (DAS) for subsurface seismic monitoring

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Distributed acoustic sensing (DAS) is a relatively recent development in the use of fiber-optic cable for measurement of ground motion. Discrete fiber-optic sensors, typically using a Bragg diffraction grating, have been in research and development and field testing for more than 15 years with geophysical applications at least 12 years old (Bostick, 2000, and summary in Keul et al., 2005). However, developments in recent years have sought to remove the need for point sensors by using the fiber cable itself as a sensor (Mestayer et al., 2011; Miller et al., 2012).

Through Rayleigh scattering, light transmitted down the cable will continuously backscatter or "echo" light so that it can be sensed. Because light in an optical fiber travels at approximately 0.2 m/ns, a 10-ns pulse of light occupies about 2 m in the fiber as it propagates. The potential of DAS is that each 10 nanoseconds of time in the optical echo response can be associated with reflections coming from a 1-m portion of the fiber (two-way time of 10 ns). By generating a repeated pulse every 100 μs and continuously processing the returned optical signal, one can, in principle, interrogate each meter of up to 10 km of fiber at a 10-kHz sample rate. Local changes in the optical backscatter because of changes in the environment of the fiber can thus become the basis for using the fiber as a continuous array of sensors with nearly continuous sampling in both space and time.

Because the technology for deploying fiber-optic cable in boreholes is well developed for thermal sensing (distributed temperature sensing, or DTS), a DAS system has the potential of having thousands of sensors permanently deployed in the subsurface, at relatively low cost. DAS systems currently use single-mode fiber, as opposed to the multimode fiber typically used for DTS, but the type of fiber does not affect deployment, and multiple fibers are easily deployed in a single capillary tube.

Recent advances in opto-electronics and associated signal processing (Farhadiroushan et al., 2009) have enabled the development of a commercial distributed acoustic sensor (DAS) that actualizes much of this potential. Unlike disturbance sensors, (Shatalin, 1998), the DAS measures the strain on the fiber to characterize the full acoustic signal. Unlike systems relying on discrete optical sensors (Bostick; Hornby et al., 2005; Keul et al.; Hornby et al., 2008), the distributed system does not rely upon manufactured sensors and is not limited by a need for multiple fibers or optical multiplexing to avoid optical crosstalk between interferometers.

We have conducted a series of field tests examining the application of this methodology in borehole and surface measurements. These tests are all part of CO_2 storage monitoring pilots and use the prototype acquisition system, iDAS, developed by Silixa (Miller et al.). The first test was undertaken at a site operated by the Southeast Carbon Sequestration Partnership (SECARB), a U.S. Department of Energy (DOE) funded pilot in storage and monitoring of anthropogenic carbon within an oil field operated by Denbury Resources in Citronelle, Alabama. The second test was part of the Otway sequestration pilot project operated by the CO2CRC

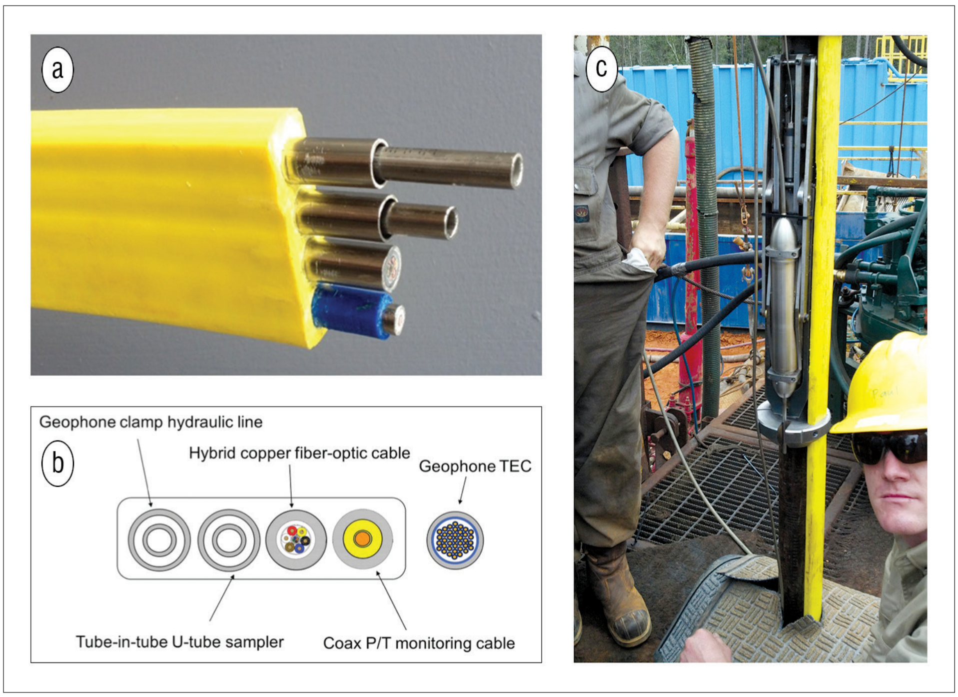

__Figure 1.__ Flatpack with DAS cable photo (a) and schematic (b). Note that the geophone tubing encapsulated conductor (TEC) cable was deployed separately from the flatback. (c) Flatpack and wall-locking geophone clamped on tubing.

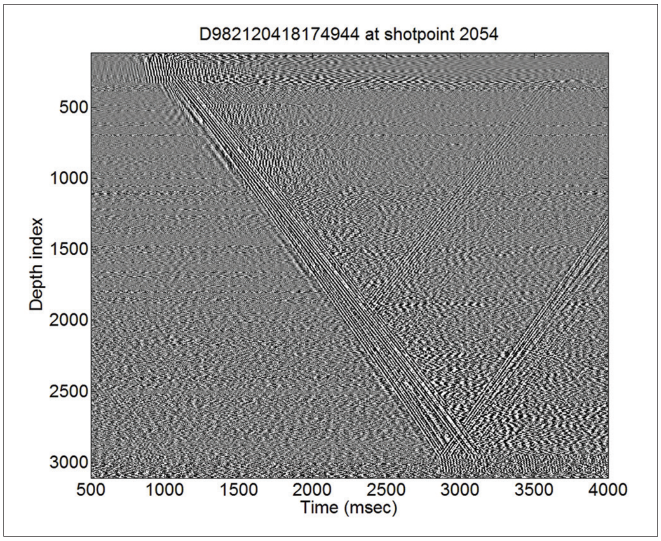

Figure 2. *DAS data from tubing-deployed MBM flatpack for a shot point approximately 100 ft from the well. There are two observed wave speeds, 1.4 km/s and 1.3 km/s; this is likely from two modes of tube waves related to the presence of a fluid-filled annulus (Marzetta and Schoenberg, 1985). Depth index is in meters.*

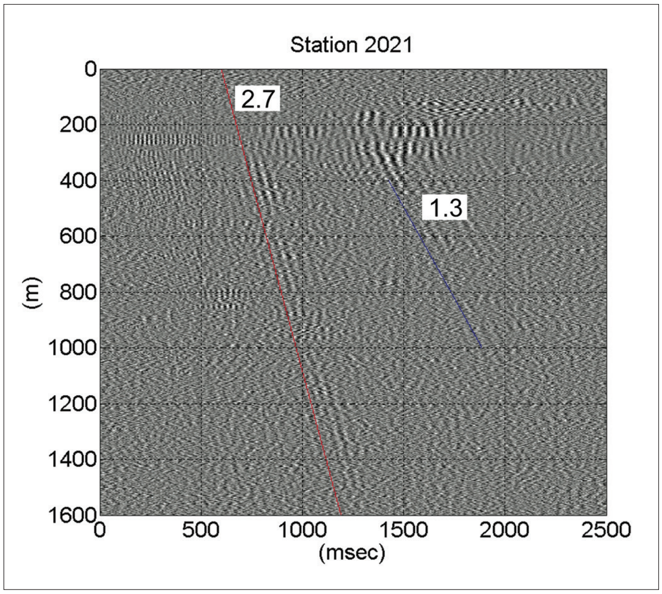

Figure 3. *DAS data from source station 2021 at Citronelle, approximately 700 ft offset from the D-9-8 sensor borehole. Estimated wave speeds for two events (red and blue lines) are labeled in km/s.*

research organization near Warrnambool, Victoria, Australia. The third test was at the Ketzin, Germany, pilot storage site currently operated by the German Research Centre for Geosciences (GFZ). In this article, we focus on the DAS data collected and the initial results from each test. Taken together, these three tests demonstrate many potential applications of DAS technology, as well as some current limitations in sensitivity as compared with conventional geophone recording. Our testing includes both borehole and surface cable data.

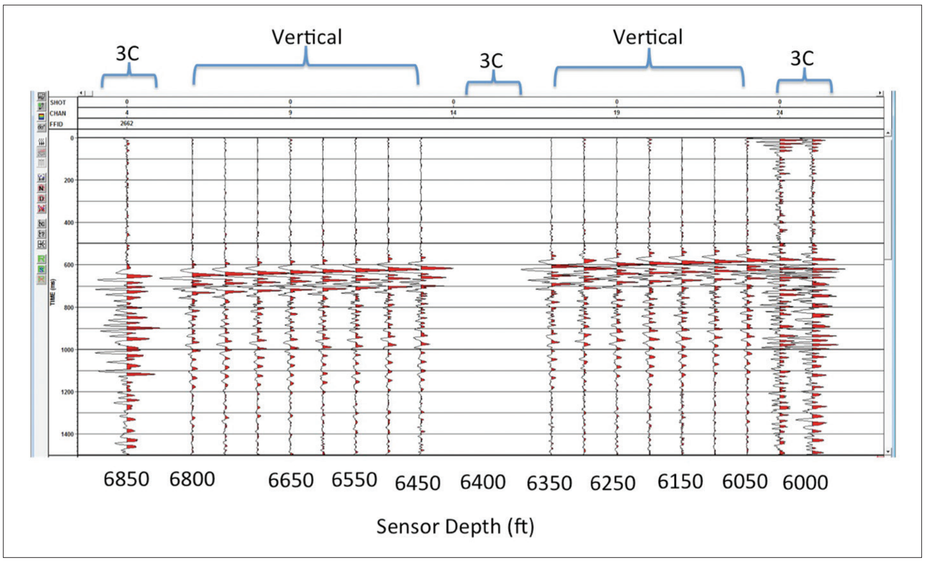

Figure 4. *MBM tubing-deployed, clamped geophone data (50-ft interval between geophones) from source station 2021 (approximately 700 ft offset) with 60-Hz notch filter and removal of bad traces. Vertical and three-component geophones are labeled with most of the 3C channels removed. A clear P-wave arrival is seen between 500 and 600 ms.*

Citronelle field test

Use of DAS at Citronelle was facilitated by the deployment of a modular borehole monitoring (MBM) package on production tubing in the Citronelle D-9-8 monitoring well which included multiple fiber-optic cables and an 18-level clamping geophone string (information available at *http://www.co2captureproject.org/reports.html)*. Deployment in March 2012, and the associated initial seismic testing, was used as an opportunity to acquire DAS data. The DAS fiber was a "fiber in metal tube" (FIMT) which was itself part of a multiconductor cable inside a molded "flatpack" (Figure 1a) which was clamped to the production tubing, in the fluid–filled annulus between tubing and casing (Figure 1b). The MBM flatpack was deployed to a depth of almost 3 km.

The DAS seismic data acquisition at Citronelle was a walkaway vertical seismic profile (VSP) recorded with an early version of the Silixa iDAS system. The initial DAS test, used a ~35,000-lb force vibroseis truck, data were processed with a synthetic linear 16-s sweep from 10 to 160 Hz. From 4 to 6 sweeps were recorded at each source point (Figure 2). A strong tube wave is observed along the entire length of the cable.

We were encouraged to observe that DAS does record seismic energy; however, the DAS recordings do not have sufficient signal-to-noise ratio for observing P-waves below approximately 1600 m (the 2.7 km/s event in Figure 3), while P-wave energy is easily seen on the clamped geophones at

6000 ft (1.8 km) to 7000 ft (2.1 km) (Figure 4). We felt this result, while not useful for seismic monitoring of the ~2.9-km deep reservoir at Citronelle, was sufficiently successful to move forward with work on improving acquisition and planning for another field test. We plan to return to the Citronelle site for further testing, where the MBM package remains installed and serves as an example of multiple instrument deployment and a test site with geophones and DAS codeployed.

Otway field test

The Otway Project is operated by the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), a joint venture with the Australian government and other industry and government organizations, to demonstrate that CO_2 can be safely transported and stored in geologic formations commonly found in Australia. More than 65,000 tons of CO_2 were injected and monitored in the ~2-km deep Warre-C Formation during the project's stage-1. Under stage-2, a second injection well, the ~1.5-km deep CRC-2, was drilled in 2010 and has been used for injection testing in the Paaratte Formation.

CRC-2 has tubing-deployed instruments, including a fiber-optic cable similar to that deployed at Citronelle, but without the flat-

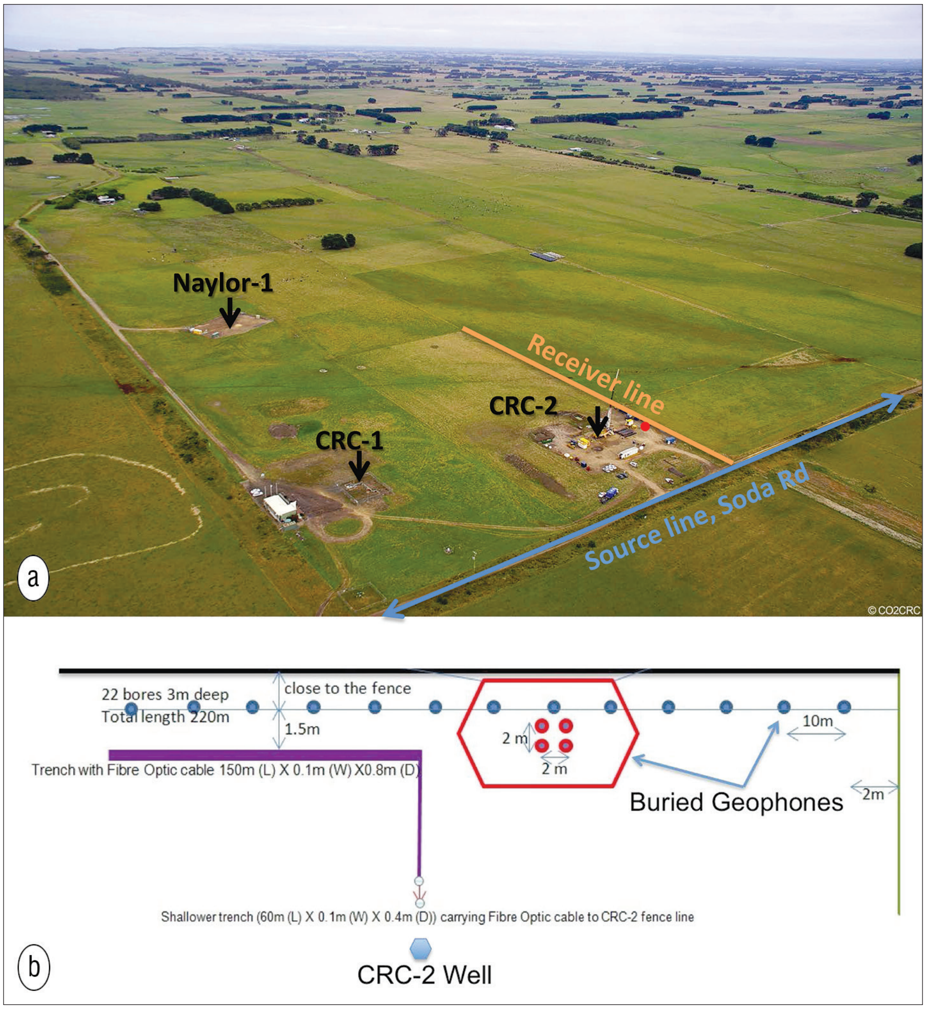

Figure 5. *(a) Otway site location. (b) Schematic plan view map of fiber-optic deployment in well CRC-2 and surface trench (purple line), along with buried geophones used for testing and the local fence line (black line). Receiver spacing along the line for conventional geophones was 10 m.*

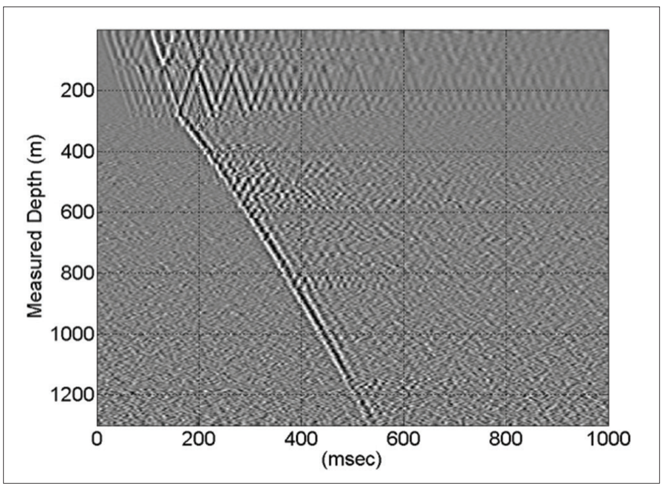

Figure 6. *Shot-gather DAS data from Otway CRC-2 borehole using weight-drop source with 41-fold stack. The top ~300 m of the well experiences multiple reverberations (which had been observed on previous geophone VSP data), but below 300 m the P-wave dominates.*

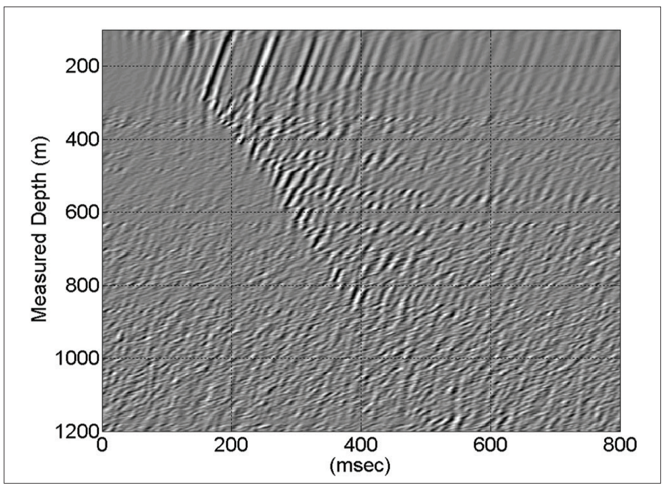

Figure 7. *Upgoing energy for the 41-fold VSP data of Figure 6, using the DAS acquisition in well CRC-2. Reflected energy is observed.*

pack. Current stage-2 planning includes testing of permanent surface seismic sensors. During one testing session, the iDAS system was brought on-site to record DAS data with a weight-drop surface seismic source. We scheduled an extra source effort to increase potential observation and use of P-wave energy.

In addition to the borehole fiber-optic cable deployed in CRC-2, a surface trench was used to deploy fiber cable and look at surface sensing with DAS (Figure 5). The surface fiber cable was looped within the trench so that two parallel lengths were recorded. A set of 25 standard geophones was placed along the same line in 3-m deep vertical boreholes with an additional 25 geophones in spike land cases planted on the surface in a parallel line.

The 720-kg weight drop source was used at an array of source locations, to allow recording of walkaway VSP-type data. One hundred fifty source points were located along the line orthogonal to the receiver line; source spacing along the line was 10 m. Walkaway VSP data were acquired using stacks of 8 shots per shot point position (2 passes of the receiver line, 4 shots in each pass). One additional shot point location (~100 m away from CRC-2) was used to acquire zero-offset VSP using an enhanced stack of 41 individual shots for DAS testing.

Otway borehole DAS data

At this site, a clear P-wave arrival can be seen (Figure 6). Separation processing of upgoing and downgoing energy was performed (Figure 7). While this upgoing section does not have enough signal-to-noise to allow imaging, the potential is evident in contrast to the previous Citronelle data test.

A conventional VSP has been recorded in the Otway CRC-2, allowing comparisons of signal-to-noise levels (Figure 8). While the two surveys had different sources and sensors, we see the difference between the two surveys, while large, is consistent with depth. This demonstrates that the DAS acquisition is not affected by the more than 1.5-km cable length. Because the DAS cable has consistent sensitivity throughout, obtaining increases in DAS signal-to-noise (S/N) ratio could allow comparable data quality to conventional geophone data.

Otway surface DAS data

The surface fiber cable deployed in a trench (Figure 5) and looped back, allowed direct comparison of the repeatability of two segments (Figure 9). We find good consistency in both amplitude and time (Figures 10 and 11)

We stacked sections of fiber-optic cable of various lengths to optimally create a single receiver. Here we use time delays corresponding to the optimum direct-wave stacking. No other processing or filtering is applied to the data. Both direct P-wave and strong ground roll are clearly observed in the data (Figure 12). A 4–16-m fiber-optic cable section provides (S/N) comparable to conventional geophones for the near offsets (less than ~400 m). However, the amplitude of the signal quickly decays beyond this range of offsets. Keeping in mind that the receiver line is orthogonal to the source line,

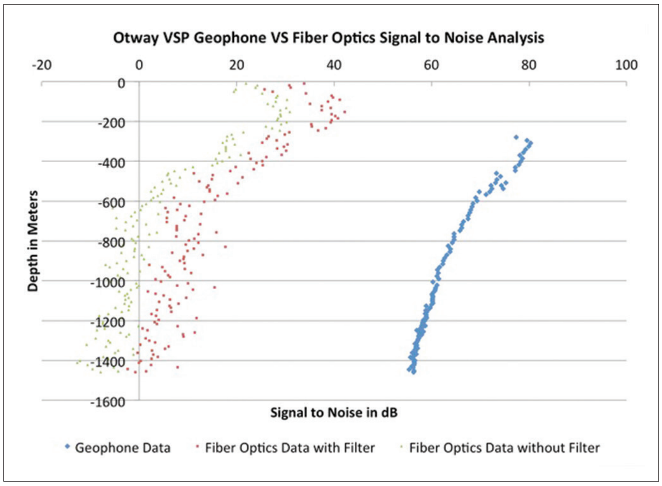

Figure 8. *Comparison of P-wave signal-to-noise (S/N) ratio for wireline, clamped geophones and tubing-deployed DAS fiber-optic from separate VSP surveys in the same well. Filtered fiber data has a band-pass filter of 5–180 Hz applied to improve (S/N). Different sources were used in the two data sets. To obtain (S/N), the root-mean-squared (rms) amplitude values for a 20-ms time window around the P-wave arrival is compared to early time pre-arrival noise.*

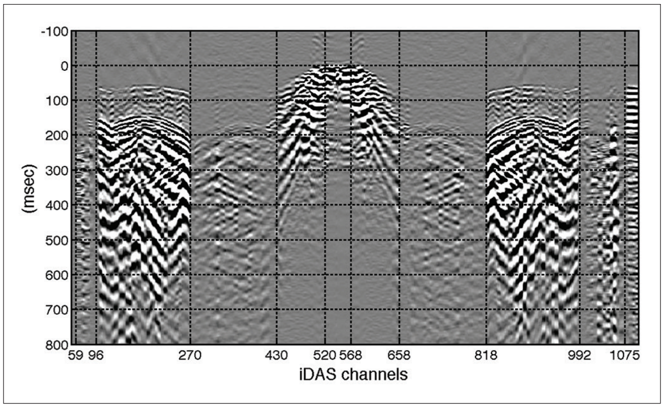

Figure 9. *DAS recording of fiber cable in loop, giving symmetric data. The iDAS channel index is 1-m spacing. The two segments of fiber cable in the main surface trench are channels 96-270 and 818-992.*

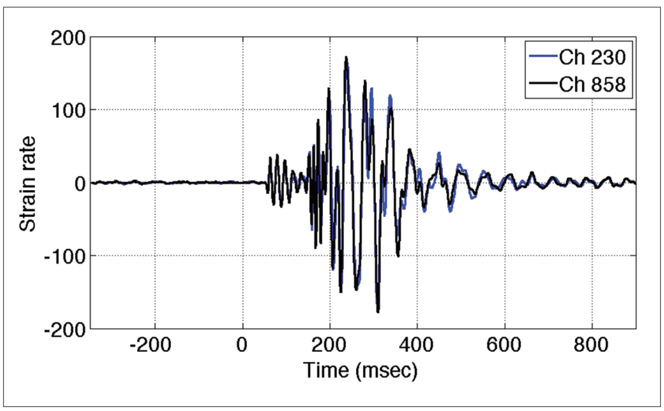

Figure 10. *Comparison of two 1-m segments of cable colocated in a surface trench.*

this fact may indicate influence of the directivity pattern of the fiber-optic cable on compressional waves.

Considering the strength of the ground roll (consisting largely of Rayleigh waves) observed in the DAS surface array, similar deployments may have utility for measuring near-surface soil properties using multichannel analysis of surface waves (MASW) techniques (Park et al., 1999). The P-wave first arrival is detectable but weak on a shot gather from the walkaway line for the source location closest to the DAS fiber array sampled at 1 m, an inline geometry similar to a traditional 2D refraction or surface-wave survey (Figure 13). A direct S-wave and a strong Rayleigh-wave package are visible on DAS shot gathers. The fundamental mode of the most useful surface-wave energy is normally dispersive across a frequency range of 19–29 Hz (Figure 13b). In general, the surface-wave data acquired with iDAS were of relatively high quality and amenable to inversion using MASW approaches.

Ketzin field test

At Ketzin, Germany, a pilot CO_2 storage project was started in 2004 by the European CO2SINK group (currently operated by GFZ) at a site with multiple monitoring wells (Wuerdmann et al., 2010; Martens et al., 2012). At the Ketzin site, fiber-optic cables were deployed behind casing in two observation wells A conventional geophone VSP was previously recorded at this site. As an R&D test, a DAS survey was recorded. The DAS survey used an accelerated weight drop source, while the conventional survey used a Vibsist source from Vibrometric.

Like the “loop” of surface cable at Otway, we were able to use a borehole loop at Ketzin, in well Ktzi 202 (Figure 14). The downgoing P-wave and many reflections can be seen and are consistent with previous conventional geophone data (Figure 15). The DAS data possess strong artifacts resulting from the dual casing completions, with the DAS fiber on the inner casing. Uncemented zones

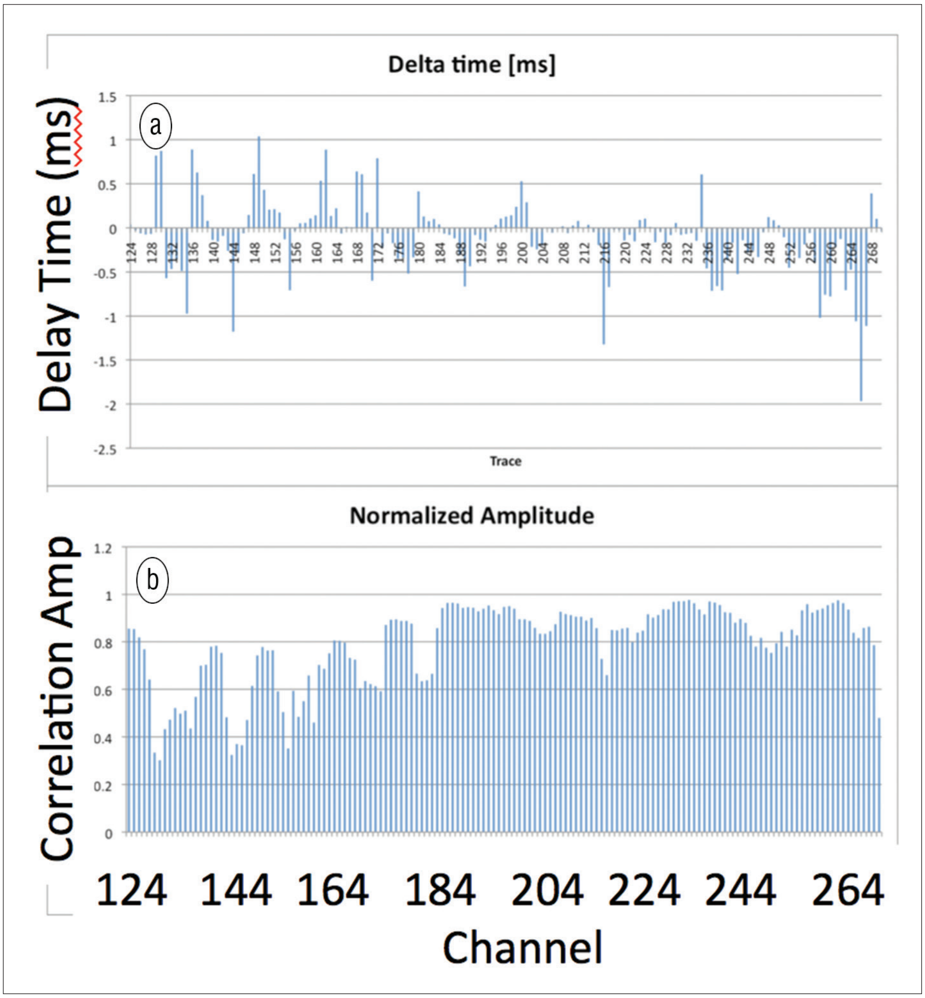

Figure 11. Cross-correlation results for two sections of surface cable colocated in trench showing, for each meter of cable (trace #), the relative time delay (a) and the normalized cross-correlation coefficient (b).

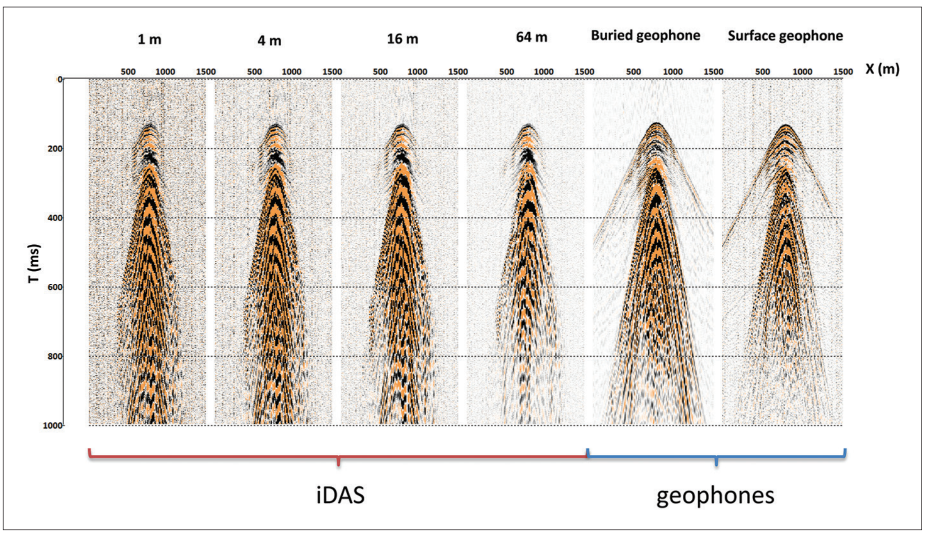

Figure 12. Comparison of iDAS and conventional geophone data in a common-receiver gather. iDAS data stacked to form 1-,4-,16-, and 64-m cable segments (taking into account time delays for the direct wave).

from 177 to 269 m and 583 to 669 m can be seen on all three data sets as a loss of seismic energy recorded (Figure 15). The generally good quality of the DAS data at Ketzin is initially attributed to the behind-casing deployment. Further analysis and testing will attempt to confirm this conclusion.

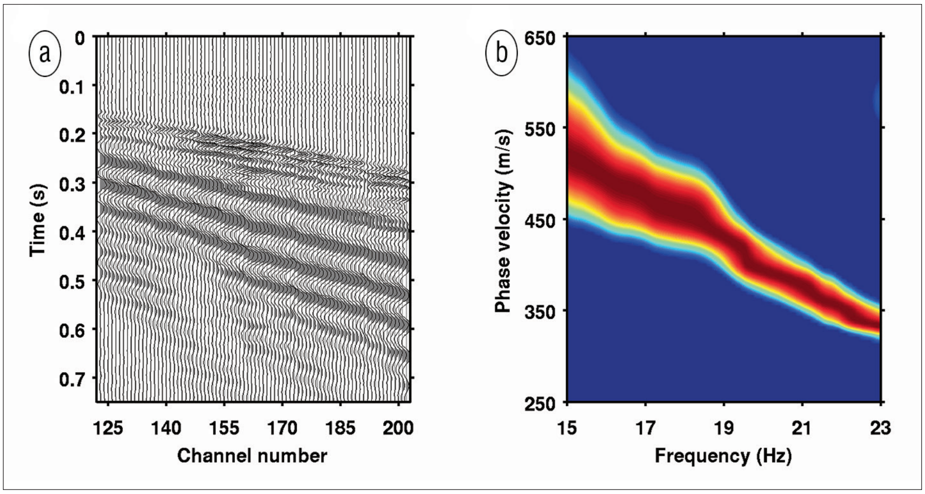

Figure 13. *Section of a trace-normalized DAS shot gather for the inline source (a) and associated normalized dispersion plot (b) calculated in the* f-k *domain. As can be seen in (a), while the refracted P-wave arrival is weak, a direct S-wave and a strong Rayleigh-wave package are visible. The dispersion plot in (b) shows the fundamental mode is normally dispersive from 19 to 28 Hz.*

Summary and conclusions

DAS seismic acquisition is a recent, and still-developing technology with many potential advantages. Three sites have been tested for DAS acquisition of borehole seismic data and one included surface seismic data.

At the Citronelle site, the fiber cable was tubing deployed to 2.9 km in a well coincident with a short string of clamping geophones. The results showed observable seismic energy, mostly tube waves, highlighting the relative low sensitivity of the fluid-coupled fiber and insufficient (S/N) to see P-waves to 2.9 km, with a standard source effort (4–6 sweeps of a vibroseis per shot point).

At the Otway site, the fiber was again tubing-deployed in a borehole, but a more energetic source and high stack counts (41 stacks of weight drop) generated more useful VSP data. DAS data from the 1500-m deep well at Otway could be compared to a previously acquired geophone VSP (with different source) and we observed approximately 40–50 dB difference in (S/N) over the entire length. While this is a large difference, improvement in DAS sensitivity is possible, and some partial (S/N) improvement can be expected with extra source effort. Additionally, the high spatial sampling of 1 m for DAS provides potential for further noise reduction.

At Otway we also ran a two-way loop of fiber in a surface trench allowing comparison of side-by-side repeatability from separate segments of cable in a surface seismic geometry. The data were found to be quite repeatable. This implies that multiple runs of fiber could be stacked together to improve (S/N), and to allow some redundancy in sensors. Furthermore, the surface cable data are shown to be useful for MASW and possibly directional in sensitivity.

At the Ketzin site, a loop of fiber cable was deployed on casing with some of the cable cemented in place. This provided the best overall data quality, again demonstrating the repeatability of separate segments of fiber cable, and showing the adverse effects of uncemented zones. Comparison with a conventional geophone VSP demonstrated both the affects of alack of cement (as expected), and the capability of DAS data to record upgoing VSP reflections over the ~700-m depth of the well.

Taken together, these tests demonstrate a variety of deployment and acquisition possibilities for DAS recording. Increased sensitivity is still a goal, especially for deep wells or long surface arrays, but both the Otway and Ketzin tests indicate that current technology can provide useful data with increased source efforts. The Ketzin tests indicate the benefit of cementing the fiber in place or deployment behind casing strings, rather than relying on fluid coupling. We expect that further testing at these sites and processing of these data will advance the development of DAS technology. The potential of large numbers of relatively inexpensive sensors, permanently deployed, opens many opportunities to be explored in the future. TLE

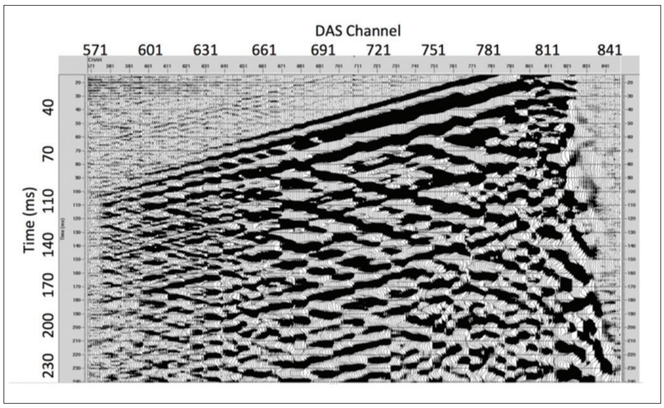

Figure 14. *Raw DAS VSP data from upper 300 m in the Ketzin Ktzi202 borehole for a stack of 92 source drops. DAS channels have 1-m spacing and the fiber cable is installed behind casing. The downgoing P-wave and upgoing reflections can be seen.*

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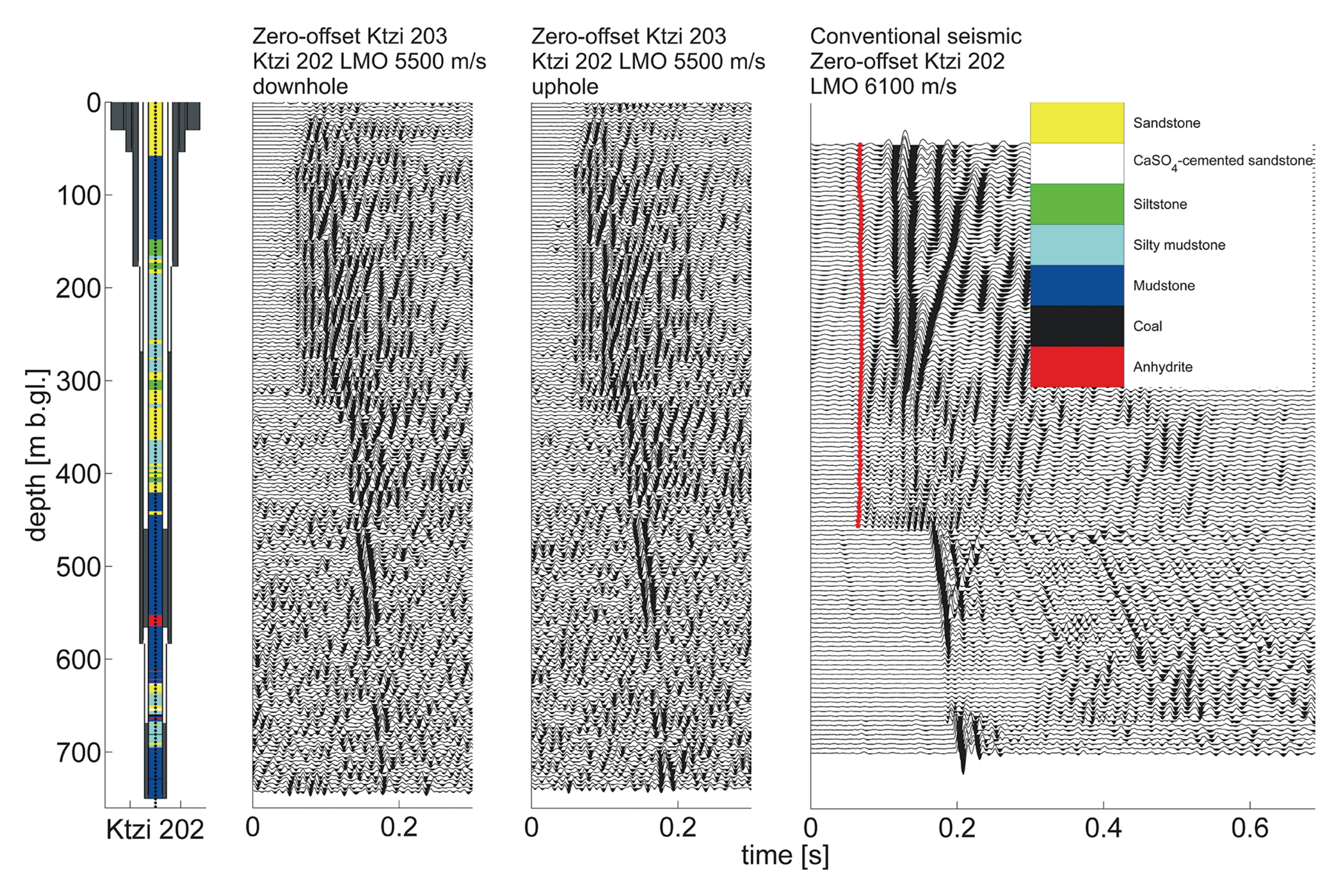

Figure 15. *(left to right) Well completion for Ktzi-202, processed VSP data from DAS downgoing fiber, upgoing fiber and conventional geophone (with well lithology insert). All seismic data sets have been aligned on downgoing P-wave, indicated by red line on geophone data using a linear moveout (LMO) velocity as labeled. The fiber data had the source at nearby well Ktzi203 while the geophone survey had the source near the sensor well Ktzi 202. Cemented segments of casing in well diagram are indicated by black sections.*

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