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Processing of Seismic-While-Drilling Data from the DrillCAM System Acquired with Wireless Geophones, Top-Drive, and Downhole Vibrations Sensors

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Abstract

We present processing details of seismic-while-drilling data recently acquired on one of the onshore wells by a prototype DrillCAM system with wireless geophones, top-drive, and downhole vibration sensors. The general flow follows an established practice and consists of correlation with a drillbit pilot signal, vertical stacking, and pilot deconvolution. This work's novelty is the usage of the memory-based near-bit sensor with a significant time drift reaching 30-40 minutes at the end of each drilling run. A data-driven automatic time alignment procedure is developed to accurately eliminate time drift error by utilizing the top-drive acceleration sensor as a reference. After the alignment, the processing flow can utilize the top-drive or the near-bit pilots similarly. We show each processing step's effect on the final data quality and discuss some implementation details.

Introduction

A drillbit emits seismic waves into the subsurface during drilling. If recorded at the surface or in nearby wells, these waves can serve as sources of information about rock properties in the well's vicinity or ahead of it. This forms the basic idea of seismic-while-drilling (SWD) with drillbit noise as a source. This technique was being actively developed in the past several decades (Staron et al., 1988; Rector and Marion, 1991; Miranda et al., 1996; Naville et al., 2004; Poletto and Miranda, 2004) by many academic and industry groups. When the seismic recordings are made near the rig at some fixed location for an extended drilling depth, they become equivalent to a reverse vertical seismic profile (VSP). The source is located downhole, while the receivers are on the free surface. The potential benefits of this technique, when compared to a standard VSP, are no interactions with drilling operations and no extra rig time. All recordings are done continuously and independently from the drilling process. Also, there is no need for a seismic vibrator at the rig site, which simplifies the acquisition and potentially allows to make the process fully autonomous.

Besides, such an approach allows observations in shallow sections normally not covered by wireline VSP surveys. Successful practical applications with this technique were reported both in onshore (Miranda et al., 1996; Naville et al., 2004; Haldorsen et al., 1995; Bakulin et al., 2020a) and offshore wells (Poletto et al., 2019; Goertz et al., 2020). There was also an earlier SWD application in the Middle East (Khaled et al., 1996). It was observed that SWD data quality might vary significantly and depend on different factors, including hardness of rocks, drillbit types, depth, drilling and surface conditions. In the best possible scenario, the data was approaching that of the conventional wireline VSP. The real-time capabilities of such recordings and some of their unique properties still make the technique very attractive.

Among the method's applications are look-ahead prediction and accurate location of the drillbit in seismic time or depth volumes to facilitate drilling optimization and potentially geosteering. With a trend in the drilling industry toward automation, the SWD data can be used as an additional source of geophysical information for integration with other data to facilitate decision-making. Apart from drilling, SWD data can be used, for example, in exploration projects for vertical travel-time estimations leading to more accurate depth maps of target horizons (Bakulin et al., 2020a).

During SWD acquisition, geophones on the surface are typically accompanied by accelerometers installed on a top-drive. These top-drive recordings are used as a drillbit source signature for data processing. While top-drive sensor records a signature of drillbit vibrations, it may be distorted during propagation along the drillstring. Also, the top-drive data is subject to surface-related noise. Alternatively, downhole vibration sensors installed near the bit can be used to record the source signal more accurately (Naville et al., 2004; Poletto and Miranda, 2004; Poletto et al., 2014). In the presence of fast telemetry, downhole data can be transferred to the surface close to real-time. Otherwise, data can be recovered from sensor memory after the drilling run is completed (non-real-time). It was shown that these sensors could provide better pilot source signals and result in higher SWD data quality.

Recently, seismic-while-drilling data were acquired during a trial testing of a prototype DrillCAM system at one of the onshore wells, as reported by Hemyari et al. (2019) and Bakulin et al. (2020a). The system consists of wireless surface geophones, top-drive and downhole acceleration vibration sensors. First processing results based on the top-drive pilot data only allows retrieval of travel-time information along the well, predicting key formations ahead of the drillbit, and providing corridor stacks similar to conventional VSP data (Bakulin et al., 2020a). This paper describes the processing sequence applied to the data in more detail and proposes a way to incorporate a downhole pilot sensor into it.

Data description

Seismic data were recorded using 2,500 vertical component single-sensor geophones installed around the rig, as shown in Figure 1. Each of the geophones was connected to a wireless transmitter sending the data to a central recording system located inside the rig pad in near real time. The initial acquisition layout had a square shape with a side length of about 1,100 m centered around the rig. Two additional orthogonal lines reached a maximum offset of 3,000 m (Figure 1). The spacing between the geophones was 25 m, both in inline and crossline directions, where applicable. Such a layout was designed for a shallower drilling depth and was used down to 2,600 ft depth. A larger geophone layout recorded deeper sections with the same number of sensors. Repositioning of wireless geophones was done during casing/cementing operations. In addition, several lines were deployed in a sawtooth-like pattern to test additional options for better noise separation in 3D RVSP during the processing, as discussed by Poletto and Miranda (2004). Nearly continuous recording with surface geophones was achieved while drilling from surface down to 10,000 ft. This amounted to 34 days of recording and resulted in ~450 GB of data every day, or totally in ~15 TB of the complete dataset.

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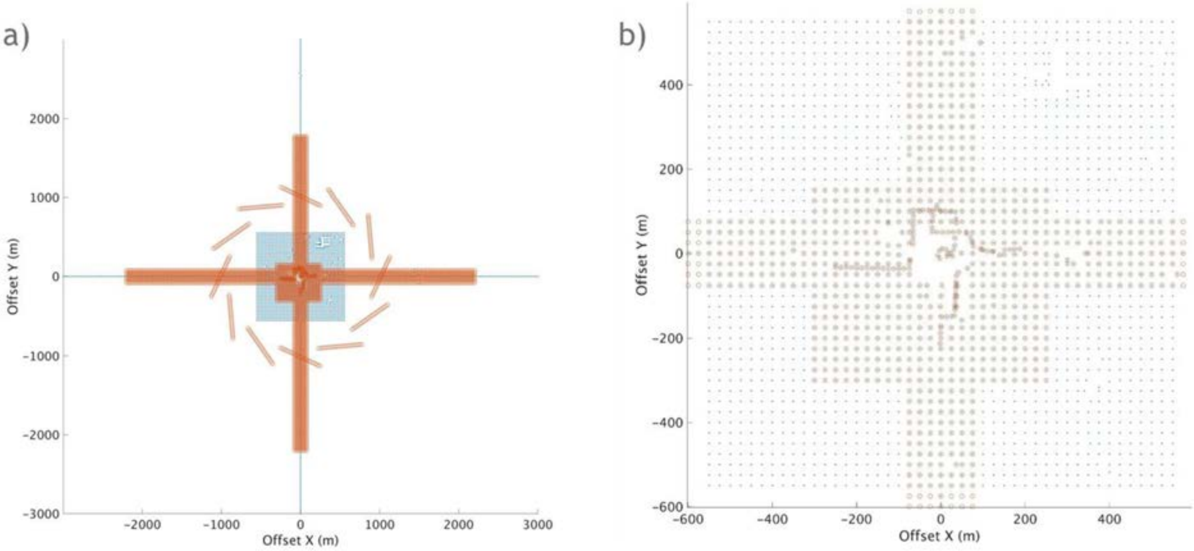

Figure 1—Acquisition geometry used in the field trial. Blue dots show receiver positions used for drilling from the surface to 2,600 ft. Red dots show the receiver pattern for deeper drilling below 2,600 ft. (a) General view; (b) Zoom into the central part of geophone layout around the rig.

The top-drive was instrumented with two sets of continuously recording three-component (3C) cabled accelerometers. Three-component memory-based near-bit accelerometer sensors were used to record the drillbit vibrations downhole in most of the drilling runs. These recordings were done continuously with a 1,500 Hz sampling rate, recording up to 120 hours of data. More details on the data acquisition can be found in Bakulin et al. (2020).

Processing of SWD data

In this trial, data processing and interpretation were performed after drilling due to the experimental nature of the prototype system. The processing phase's main goals were to assess the overall feasibility of the system, verify the quality of the recorded data, and pave the way to potential future applications. Processing was done using a commercial software system designed for surface seismic processing. Several additional processing modules were developed in-house specifically for the seismic-while-drilling application. The general processing flow is shown in Figure 2.

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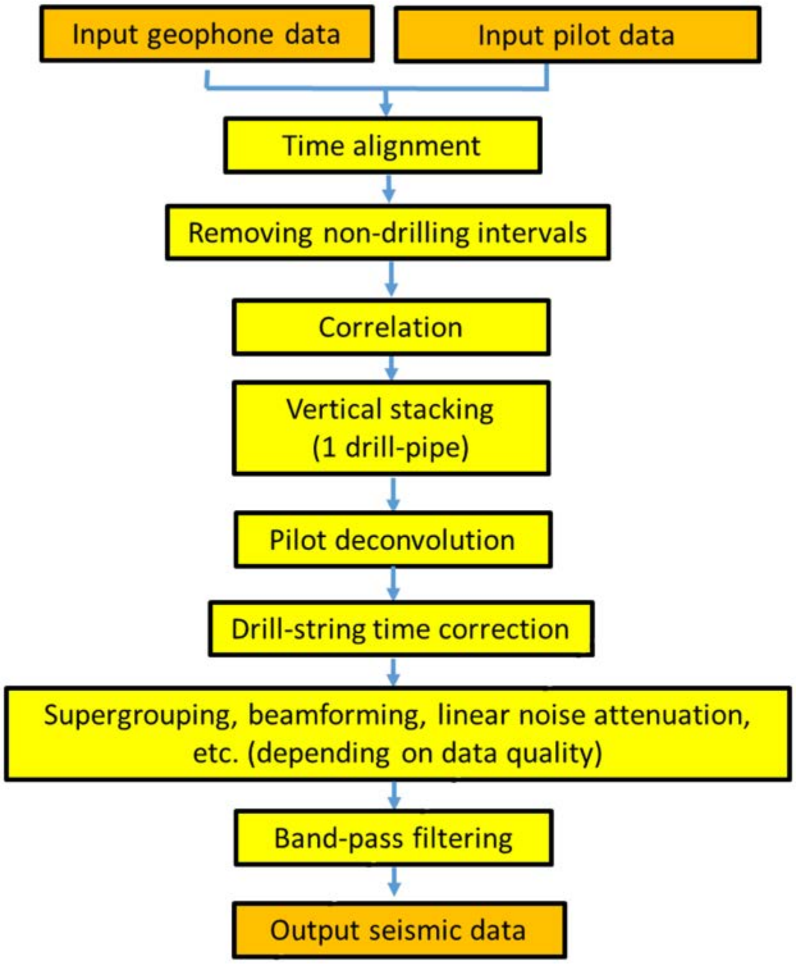

Figure 2—Flowchart describing processing of the recorded seismic-while-drilling data.

Time alignment between top-drive sensor and downhole tool

Accurate and consistent time is essential to correctly process surface geophone data and pilot signal data representing drillbit source signature. DrillCAM system receives time-series data from four independent components: seismic recorder assembling data from surface geophones, top-drive sensor recorder, downhole memory sensor, and electronic drilling recorder capturing all drilling parameters. Ideally, all the components should be accurately synchronized before and during acquisition. In the first trial, we used separate recorders and timekeeping. Therefore, we had to rely on the processing phase to achieve accurate time alignment. The geophones and top-drive recordings were both GPS synchronized. It turned out that one of the systems was off compared to another by constant 18 leap seconds due to GPS versus UTC times. The downhole recordings were done using memory-based tools with an internal clock subject to significant drift and initial time delay. The drift observed in this trial was quite significant, reaching 30-40 minutes at the end of each drilling run (60-120 hours). Since the seismic data are sampled at 2 ms interval, the required synchronization error should be at least of similar order or smaller.

Without accurate time corrections, downhole recordings could not be used as pilot data for seismic-while-drilling. A novel data-driven automated two-step alignment procedure was developed by Egorov et al. (2020) to perform the downhole time correction using a GPS-synchronized top-drive vibration sensor as a reference. The first step finds the delay time and linear drift using a global optimization approach. The second step estimates nonlinear drift using time-variant crosscorrelation. Alignment precision of a few seconds after the first step becomes a few milliseconds after the second step, as demanded by seismic while drilling. The synchronization accuracy can be assessed in Figure 3, where the top-drive and downhole pilots'

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autocorrelations after the alignment are shown. The drilling high-amplitude intervals and non-drilling time, characterized by low energy windows, match perfectly in both pilot's recordings. Finally, the drilling logs can also be aligned to the surface seismic data using the same automated procedure using the downhole or the top-drive recordings as a reference.

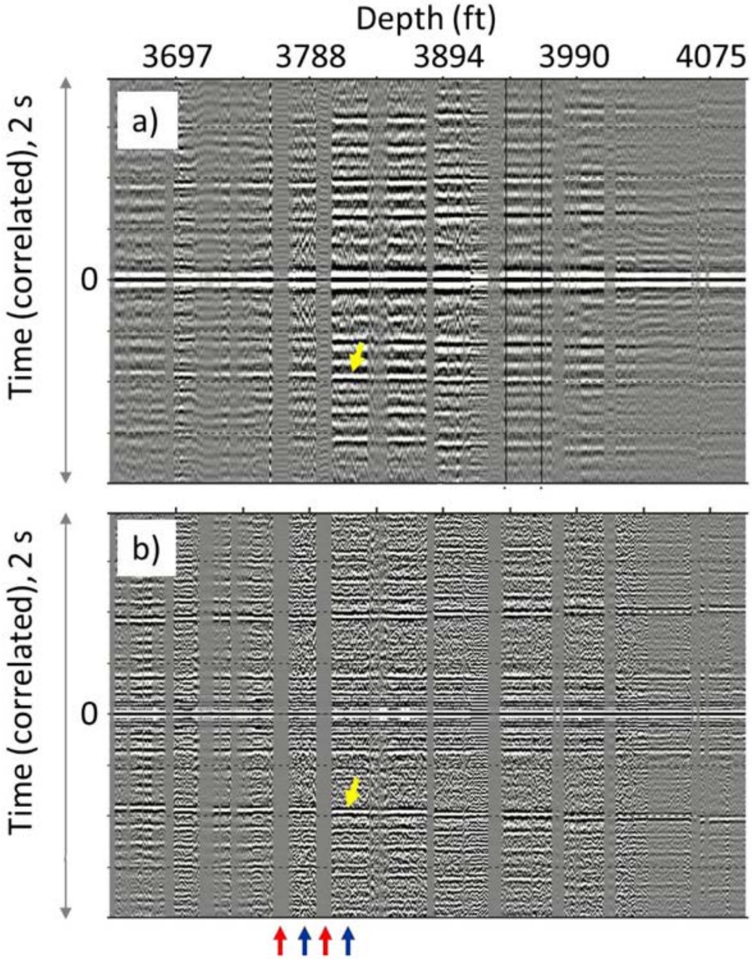

Figure 3—Autocorrelation of pilot signals after time alignment step from (a) top-drive sensor; (b) near-bit sensor. Note the perfect match between non-drilling (red arrows) and drilling (blue arrows) intervals in both sensors. Yellow arrows indicate long-period drillstring multiples.

Removing non-drilling intervals

As shown in Figure 3, continuous data acquired during the trial contained both drilling and non-drilling intervals. Since we are using the drillbit vibrations as a seismic source, only drilling parts are useful. In contrast, non-drilling data are dropped from the processing and analysis. During the first stage, the selection of traces was made based on a drilling indicator from the electronic drilling recorder, which keeps around 58% of the originally recorded data. Additionally, criteria based on a more detailed analysis of different drilling parameters (rate of penetration (ROP), weight on bit (WOB), revolutions per minute (RPM), drillstring length, etc.) were introduced to remove suspect and noisy intervals. Figure 4 shows this editing result, where traces with extreme ROP and WOB values were removed together with the erroneous string length records. The remaining 52% of the recorded data (~8TB) were used for further processing.

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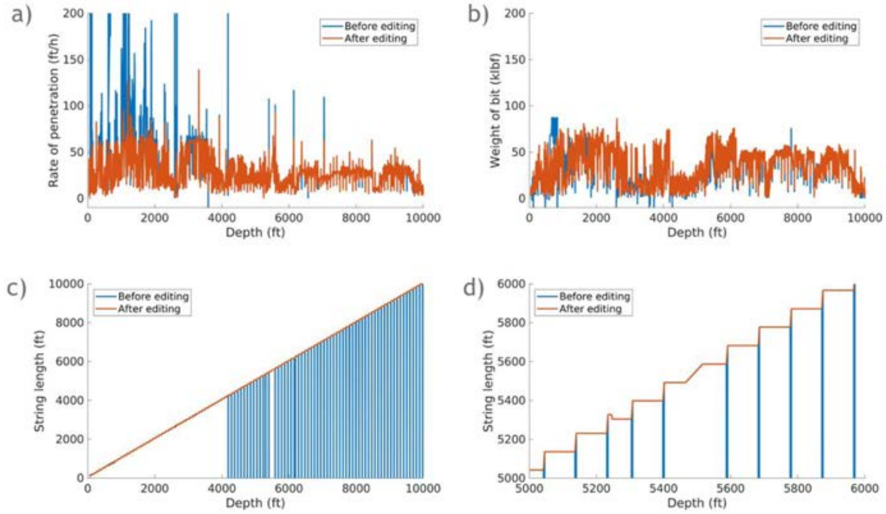

Figure 4—Editing data to remove non-drilling intervals and other records suspected of errors in drilling parameters.

Correlation of SWD data with the pilot signal

To transform continuous seismic records to standard impulse-like seismograms, a correlation with the pilot signal similar to a vibroseis technique should be performed. Unlike a vibroseis sweep, the drillbit source signature is a priori unknown, random, complex, highly variable, and not readily extractable from a single trace of the SWD geophone survey. Figure 5 shows raw data from a central East-West line recorded at the surface during drilling at 3,860 ft depth. One can clearly observe intense seismic events propagating away from the rig located in the middle of the seismic line and generated by the rig structure's vibrations. Correlation of the raw data with the top-drive pilot reveals the surface waves usually observed in conventional land seismic data. Additionally, at this step, the autocorrelation of the pilot signal is performed, as shown in Figure 3 to be used later during processing.

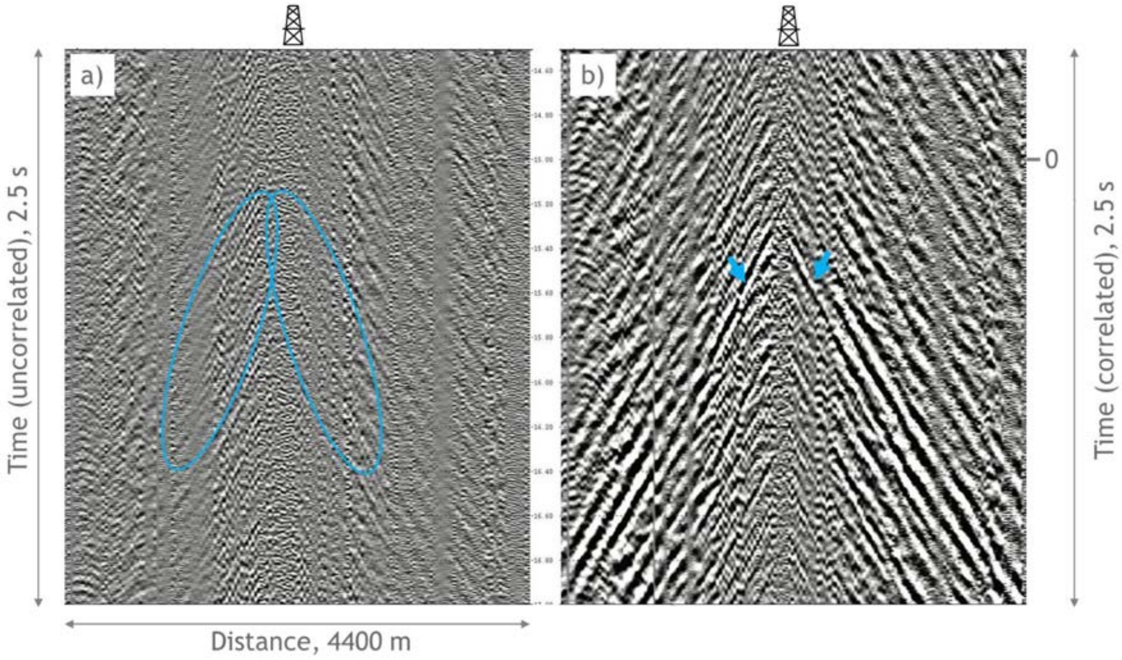

Figure 5—Raw geophone data recorded while drilling at 3,860 ft depth from a central West-East line shows continuous seismic events (marked by blue ovals) coming from the rig located in the center of line (a). Correlation with the top-drive pilot signal compresses the signal as shown by blue arrows and produces conventional impulse seismograms with the source at the bit's position (b).

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Vertical stacking of SWD signal over single drill pipe length

A significant amount of energy observed in the seismic records while drilling is a noise coming from the rig's structure, mud shakers, engines, vehicles, generators, etc. The main target signals of the SWD technique are direct arrivals and reflected waves induced by the drillbit in the subsurface and recorded at the surface. To increase the level of these signals, a vertical stack of the correlated data over a specific drilling depth interval is performed. We applied a stack over one drill-pipe length equal to 30 ft, though different intervals can be used depending on drilling conditions. Since the seismic wavelength is usually several times larger than this length, such stacking does not significantly deteriorate the final results. In the considered case with the penetration rate of 30 ft/h, they combine one hour of recordings into a single gather. The data after such stacking reveals a weak direct arrival event, as shown in Figure 6a. In addition to correlations, the pilot signals' autocorrelations are also vertically stacked for the same drilling interval. Since three drill pipes are added together at each time, we observe 90-ft-long segments with a constant drillstring length in Figure 4d. The propagation time from the drillbit to the top drive remains constant during these periods, manifested as horizontal stripes of drilling periods in Figure 3. Consequently, the pilot signals' autocorrelations can be coherently stacked for up to 90 ft drilling intervals without any deterioration. Such stacking helps to increase the pilot's signal-to-noise ratio and construct more stable deconvolution operators required during the next processing step.

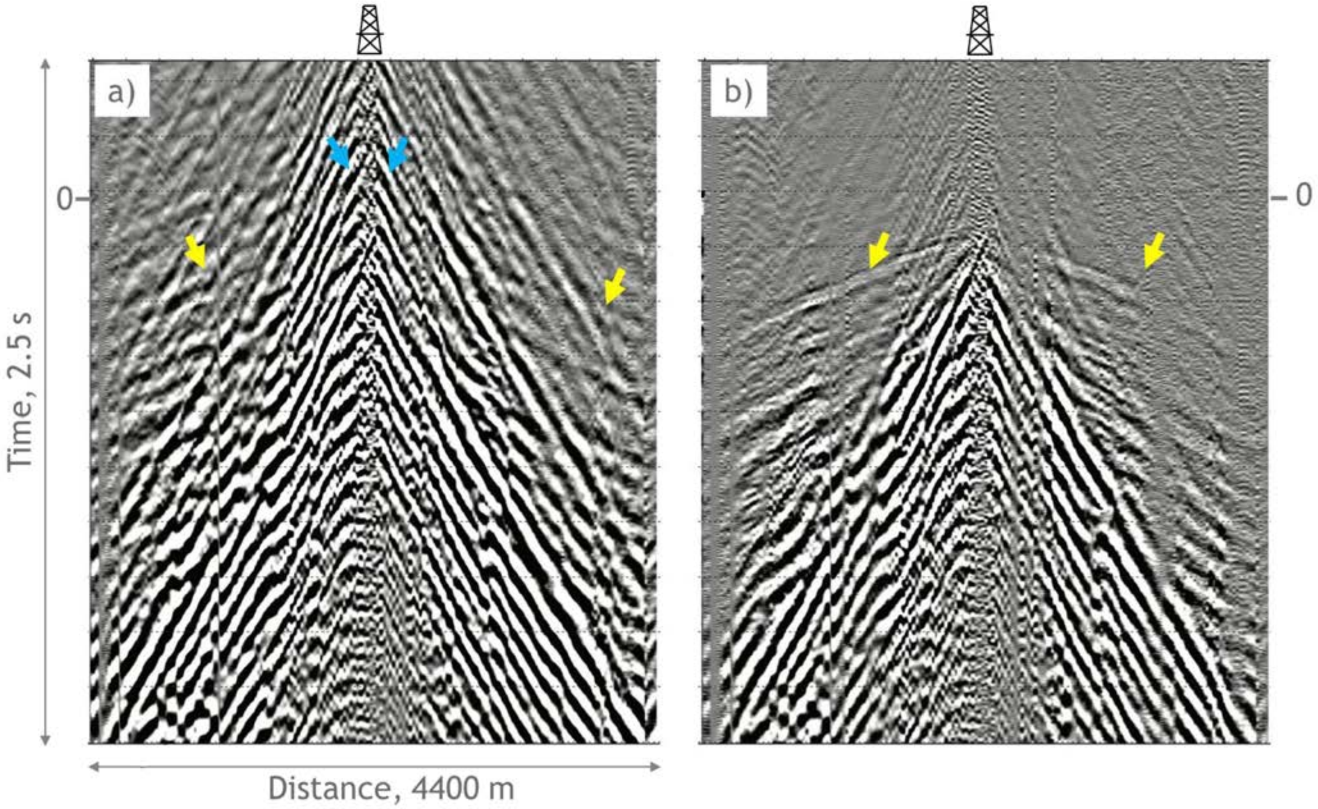

Figure 6—Stacking of correlated data over one 30 ft drill-pipe (~1 hour of recordings) increases the signal-to-noise ratio and reveals direct arrival event, marked by yellow arrows (a). Blue arrows show correlation-related noise preceding direct arrivals. Pilot deconvolution result (b) attenuates this noise and provides more clear and focused direct arrivals.

Deconvolution of SWD with the pilot signal (pilot deconvolution)

In addition to direct arrival from the bit, pilot traces recorded either by top-drive or near-bit sensors also contain additional events such as multiples caused by the ends of the drillstring (top-drive and drillbit) as well as internal boundaries within (drillstring joints, bottom hole assembly (BHA), etc.) Deconvolution, applied to the correlated data, shortens the source signature and attenuates these multiple reflections and

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other delayed and periodic components recorded by the pilot sensors. Following Poletto and Miranda (2004), we construct an operator for the deconvolution from stacked autocorrelations of the pilot traces using Wiener least-squares predictive filtering with unit prediction distance. The operator is reversed in time to remove anticausal components in the pilot autocorrelation and associated events in correlated data. The operator length is calculated to include the BHA and pipe short- and long-period multiples propagating in the 1D drillstring transmission line and is equal to two seconds in the current example. The pilot deconvolution applied to the correlated and stacked data removes the pilot-filtering effect reversed in "backward times" in the data. It strongly attenuates nonphysical seismic events before first arrivals, as shown in Figure 6b.

Drillstring time correction

Since the top-drive sensor measures the pilot signal from the drillbit after its propagation along the drillstring, it has a delay approximately equal to this drillstring propagation time. The downhole pilot, after alignment with the top-drive sensor, has the same time delay. Hence, the seismic data after correlation with any of these pilots should be corrected for this delay. We can use long-period multiples bouncing between the top-drive and the drillbit in the drillstring to estimate this correction. Figure 7 shows autocorrelated, stacked, and deconvolved top-drive pilot traces. The long-period multiples of interest are observed as strong dipping events. By estimating the slope, a drillstring correction velocity of 4,880 m/s was obtained.

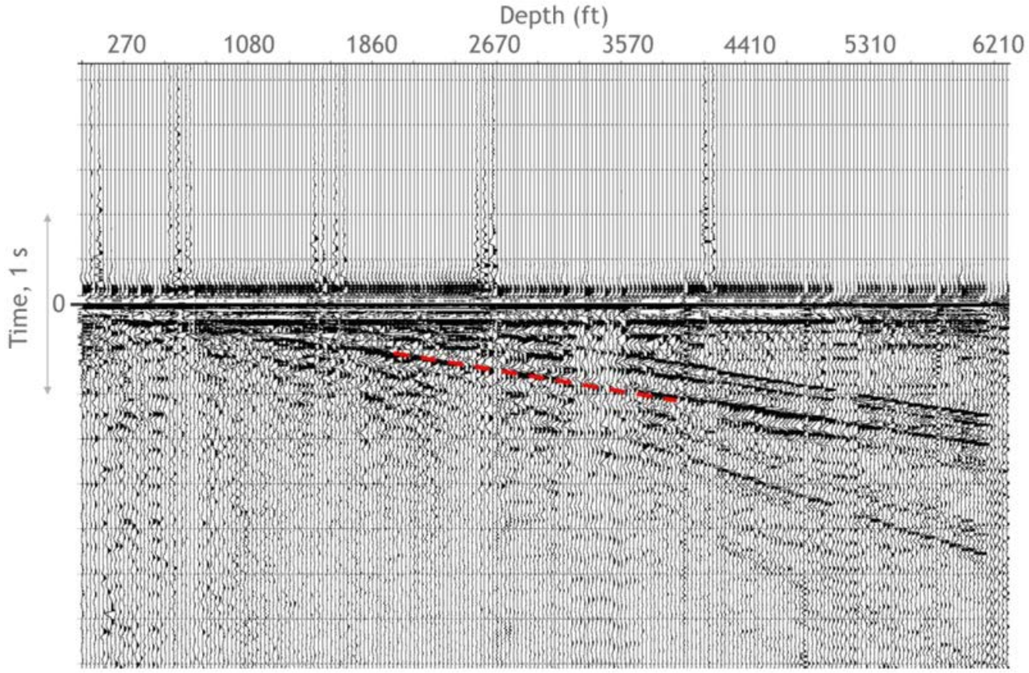

Figure 7—Top-drive pilot data after autocorrelation, stacking, and deconvolution. The red line shows a long-period multiple event providing a drillstring velocity of 4880 m/s.

Noise removal and supergrouping

Seismic acquisition in the study desert area is usually done with 9-72 geophone arrays to enhance weak seismic reflections and reduce scattering noise caused by complex near surface. SWD data was acquired with single sensors. Even after processing above, the signal-to-noise ratio requires improvement using typical land data processing techniques. As an example, a result of straightforward stacking or supergrouping of seven adjacent receiver lines along the cross-line direction (Figure 8a) shows a notable improvement of the direct arrival event in comparison to the single-sensor line shown in Figure 6b. More advanced noise attenuation, grouping, and beamforming techniques can be further applied to improve the signal-to-noise ratio of land SWD data (Bakulin et al., 2018a; Bakulin et al., 2018b; Bakulin et al., 2020b).

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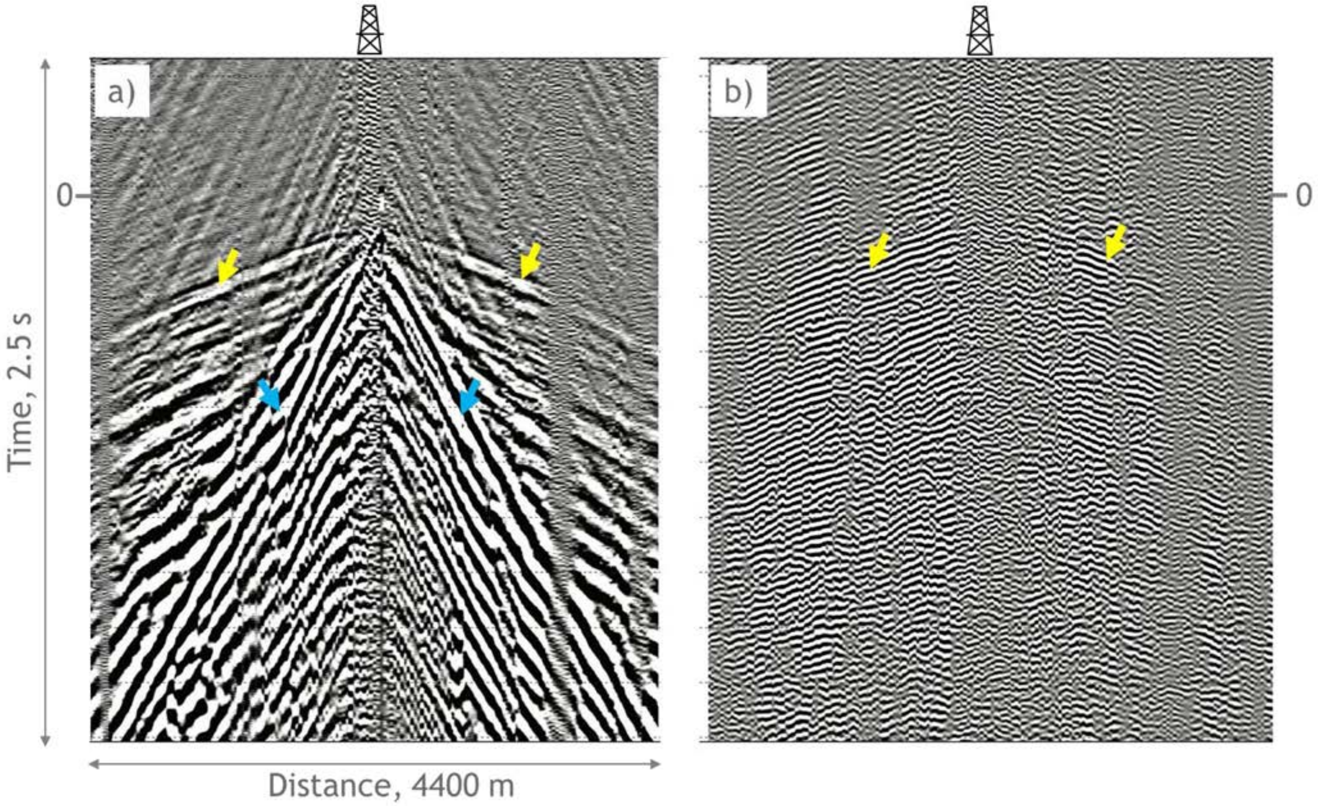

Figure 8—(a) SWD common-bit gather after supergrouping or stacking of seven adjacent lines produced using a top-drive pilot. Note improvement of the direct arrival event marked by yellow arrows in comparison to the single-sensor line shown in Figure 6b. (b) Same gather but after additional application of bandpass filtering. Note removal of low-frequency rig-related noise marked by blue arrows. The filtered data contain direct arrivals marked by yellow arrows and reflections arriving at later times.

Bandpass filtering

The surface waves propagating from the rig have relatively low-frequency content (Poletto and Miranda, 2004). Effective attenuation of these waves can be achieved by low-cut filtering. Additional filtering of higher frequencies can be applied to attenuate high-frequency noise. An example of applying a trapezoidal filter with a passband between 30 Hz and 50 Hz is shown in Figure 8b. The surface-related noise is suppressed, whereas the direct arrivals and reflection events become more visible.

Discussion

The general processing steps applied to the recorded seismic-while-drilling data follow a typical approach described by Poletto and Miranda (2004). This work's main novelty is the usage of a near-bit memory-based sensor delivering an alternative pilot signal to be used for correlation with surface data. Despite the large time drift of the internal sensor clock, we managed to align with the seismic data using top-drive pilot as a reference. After the alignment, the processing sequence becomes similar for both pilots. For comparison, Figure 9 shows a result similar to Figure 8, but obtained using the near-bit pilot. Observe more focused direct arrivals than the top-drive data (compare Figures 8a and 9a) as marked by yellow arrows. Also, the noise level is lower before direct arrivals and at near offsets (compared 8b and 9b). We note that all presented results show data acquired when drilling at 3,860 ft depth. More detailed analysis and comparison of the results for the entire well is a topic of future publications.

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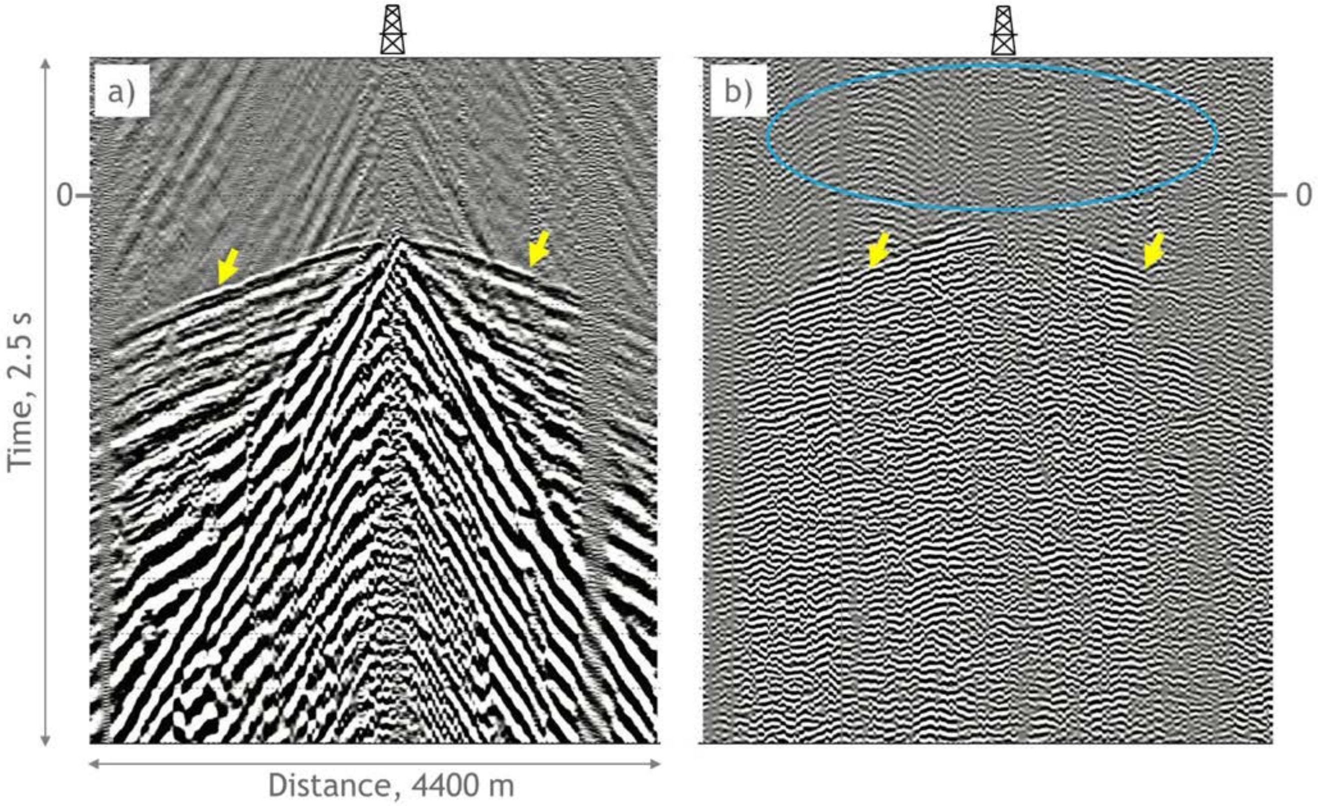

Figure 9—Same as Figure 8, but obtained with the near-bit pilot. Note more focused direct arrivals than the top-drive data (Figure 8a) as marked by yellow arrows and lower noise level before direct arrivals (areas inside blue oval to be compared with Figure 8b).

Conclusions

We describe a case study and present a detailed processing flow applied to obtain robust seismic-while-drilling data acquired during the first trial of the DrillCAM system. The system comprises of wireless geophones, a top-drive sensor, and a downhole near-bit accelerometer. The processing flow uses data from the top-drive and downhole recordings as pilot signals for correlation and deconvolution of the surface geophone data. A top-drive sensor was typically used in many previous case studies and some commercial systems available in the past. It was generally observed that the data quality of such systems is quite variable. Several studies suggested that the downhole sensor should provide a drillbit pilot signal of better quality. In this work, we use one of such memory-based sensors commercially available on the market. Due to a significant time drift, an essential step is time alignment of this sensor to geophone data with an accuracy of around several milliseconds. This was achieved with a novel data-driven approach using the top-drive pilot data as a reference. After the alignment, both pilot sensors were successfully applied to process seismic data acquired while drilling using the same processing sequence. Initial analysis of the results shows some benefits of the near-bit pilot recordings resulting in more coherent direct arrival events and reduced noise level.

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