Seismic-while-drilling applications from the first DrillCAM trial with wireless geophones and instrumented top drive

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Abstract

Advanced geophysical sensing while drilling is being driven by trends to automate and optimize drilling and the desire to better characterize complex near surface and overburden in desert environments. We introduce the DrillCAM system, which combines a set of geophysical techniques from seismic while drilling (SWD), drill-string vibration health, estimation of formation properties at the bit, and imaging ahead of and around the bit. We present data acquisition, processing, and initial application results from the first field trial on an onshore well in a desert environment. In this study, we focus on SWD applications. For the first time, wireless geophones installed around a rig were used to acquire continuous data while drilling. We demonstrate the feasibility of such a system to provide flexible acquisition geometries that are easily expandable with increasing bit depth without interference from drilling operations. Using a top-drive sensor as a pilot, we transform the drill-bit noise into meaningful and reliable seismic signals. The data were used to retrieve a check shot while drilling, make kinematic look-ahead predictions, and obtain a vertical seismic profiling corridor stack matching surface seismic. Robust near-offset check-shot signals were received from roller-cone and polycrystalline diamond compact (PDC) bits above 7200 ft after limited preprocessing of challenging single-sensor data with supergrouping. Detecting signals from deeper sections drilled with PDC bits may require more advanced processing by using an entire 2D spread of wireless geophones and downhole pilots. The real-time capabilities of the system make the data available for continuous data processing and interpretation that will facilitate drilling automation and improve real-time decision making.

Introduction

Seismic while drilling (SWD) with a drill bit as a source has been demonstrated to deliver valuable real-time information not readily available from other sources (Rector et al., 1988; Naville et al., 2004; Poletto and Miranda, 2004). Significant challenges associated with instrumentation and signal levels were identified and partially overcome, whereas the incorporation of geophysical information by drillers remained limited (Naville et al., 2004). Two critical business perspectives may call for a renewed push of these techniques: one in support of advanced drilling and another in support of modern exploration.

In recent years, the drilling industry put significant emphasis on optimization and automation as critical directions for the future. Optimization and automation require a step change in sensing capabilities and real-time analysis. Self-driving cars are enabled by a myriad of new sensors monitoring the surrounding environment in 360° and generating enough information for accurate road decisions. Likewise, automated drilling demands measuring and inferring a large amount of data to characterize conditions near and ahead of the bit. To appreciate the step change, one needs to compare the number of sensors and capabilities of regular cars and self-driving cars. A light detection and ranging sensor at the top of a self-driving vehicle beams 1.4 million laser points per second to create a 3D map of the surroundings. A similar trend is emerging in drilling that is manifested by the growing availability of fast electromagnetic (EM)-based telemetry and increased popularity of measuring drilling parameters and vibrations near the bit. However, existing measurements are still insufficient to achieve robust optimization and automation. This drilling-wide push for better instrumentation could be a sign for the geophysical community to revisit what we can do for drilling, especially in the context of new instrumentation advances and improved computational algorithms, including those based on artificial intelligence. DrillCAM, introduced by Al-Muhaidib et al. (2018), was designed to fill this sensing gap to assist drilling optimization and automation and to address specific exploration challenges. SWD is one of many components of the system. Still, the scope is broader and includes additional geophysical measurements and techniques to address drilling optimization and automation, from drill-string vibration health, to the estimation of formation properties at the bit, to imaging ahead and around the bit (Bakulin et al., 2019a).

From an exploration perspective, increased emphasis on low-relief structures and stratigraphic traps demands unparalleled accuracy from surface seismic to map deep structures with relief less than 30 ms or 60 m (Bakulin et al., 2017). This is not a small task. The bulk of the structural uncertainty is believed to come from difficult-to-capture velocity variations in the complex near surface and shallow overburden. Unfortunately, for economic and technical reasons, these sections have few velocity controls. Most companies stopped doing uphole programs for near surface, and wireline logging is restricted mainly to reservoir zones. Despite drilling a large number of onshore wells, the gap in near-surface and overburden characterization remains unaddressed and is growing as exploration expands. While cost is one major factor, there are other technical factors at play that prevent us from closing the gap. For example, conventional borehole geophysics in cased holes may not deliver reliable results in shallow 0–4000 ft sections where multiple casing strings are present. Another technical challenge is the large diameter of shallow sections (22–42 in),

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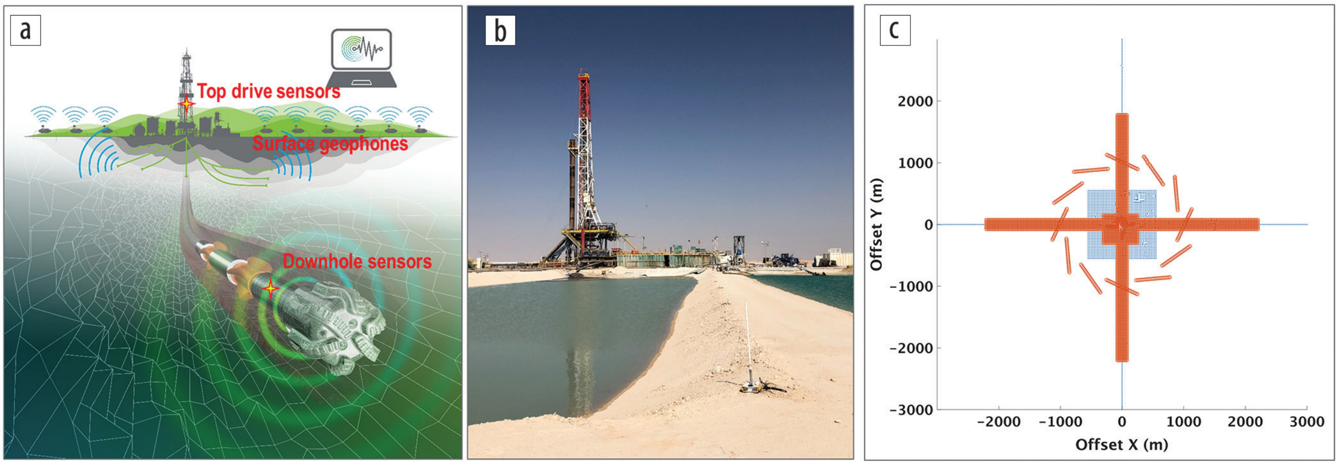

Figure 1. (a) Sketch outlining the main components of the acquisition system. (b) Layout of the field trial at an onshore rig. A line of wireless geophones with antennas can be seen going toward the rig. (c) Adaptable acquisition geometries increasing aperture with bit depth. The blue dots show receiver positions used for drilling from the surface to 2600 ft. The red dots show the receiver pattern for deeper drilling below 2600 ft.

which often does not allow reliable wireline logging. In contrast, while-drilling geophysical measurements are free from these limitations and do not consume additional rig time. Therefore, they make sense for addressing near-surface and overburden characterization gaps in exploration.

We describe an integrated case study from the first field trial of the system that targets the following objectives:

- verify the feasibility of acquiring seismic signals from the drill-bit source in real time by using wireless surface geophones;
- evaluate drill-bit signal strength for the drilling window of 10,000 ft by using roller-cone and polycrystalline diamond compact (PDC) bits;
- validate various pilot measurements of drill-bit signal, including seismic accelerometers placed downhole near the bit as well as at the top drive on the surface;
- compare and evaluate the value of information obtained with top-drive and downhole sensors; and
- collect continuous data in the depth interval of 0–10,000 ft to characterize formation properties and drilling dysfunctions as the first step toward approaches based on artificial intelligence.

In this study, we summarize the experiment layout with acquisition details, demonstrate the quality of acquired data, and focus on results achieved by using SWD applications with the top-drive accelerometer sensor.

Data acquisition for a field trial on an onshore well

Figure 1a shows schematics highlighting key initial sensing components evaluated in the considered prototype system, including surface geophones, rig sensors, and downhole sensors at the bit, all continuously recording together.

Since an integrated commercial system is not available on the market, we identified the best fit-for-purpose components and assembled a prototype system from the available parts. Most were recent arrivals, and their testing represented an additional technology objective. A typical onshore well was selected for the trial (Figure 1b). The complete data set was acquired from the surface to about 10,000 ft by using roller-cone (34, 28, and 22 in sections) and PDC bits (22 and 16 in sections).

Surface seismic sensors. Surface sensors for SWD applications need to satisfy three essential requirements: (1) they need to be lightweight and preferably cableless for ease of operation, (2) they need to be adaptable for different geometries with easily modifiable receiver spacing and areal coverage, and (3) they need to enable continuous recording in real time without the need for equipment and physical data retrieval.

Out of the different options, it is clear that wireless receivers transmitting data in close to real time, as opposed to blind memory nodes, satisfy all three requirements. As a result, we opted to trial test one of the commercially available wireless systems. Capturing near and far offsets while allowing for denser receiver sampling within the rig area dominated by noise is essential for processing. This requirement is best met with a lightweight cableless system. Likewise, the same features enable easy deployment of adaptable geometries (Figure 1c). While drilling shallow sections, 2500 wireless stations were deployed, covering a smaller aperture with denser sampling. In contrast, deeper sections were recorded with a larger layout and sparser sampling by using the same number of sensors (Figure 1c). Sensor repositioning was achieved during casing/cementing operations with limited human resources (Figures 2b and 2c). The final and most critical aspect for the system is the ability to collect data in close to real time for quick delivery of various solutions for drilling. This last aspect was quantified by measuring the average distribution of collection times (Figure 3) that indicate when data arrive at a central recorder. Data come in two main batches. At 68 s after the end of the trace, all of the data are available at the central rig recorder for real-time processing. This is an excellent result that satisfies the near real-time needs of SWD while enabling operational efficiency and flexibility. Collection settings were set to maximize data recovery, whereas even faster harvesting times are achievable with minimal losses, which are still acceptable for DrillCAM applications (Bakulin et al., 2019a).

Wireless stations are powered by removable batteries that can be swapped easily. Since charging status is also monitored from the central recorder in real time, battery swaps can be optimized to occur during nondrilling periods and daylight hours. Since conventional geophones are connected to the local wireless stations by a short cable, the sensor itself remains inserted during the swap. It maintains consistent and repeatable coupling throughout the cycle of acquisition. Single geophones were used in this trial; however, geophone arrays can be similarly connected to the same wireless stations and maintain all listed advantages (Bakulin et al., 2019a).

Figure 2. (a) Wireless geophones placed within the rig perimeter. (b) Wireless geophone stations are easy to deploy in the open desert. (c) Transmitting over jebels requires additional radio towers. (d) Top-drive sensors (marked by arrows) are attached to the body of the top drive. The position of the sensors, with respect to the rest of the equipment, can be seen in (e). (f) The downhole tool placed inside the carrier bit sub is shown at the surface. BHA, including the carrier sub and tool, is seen (g) without and (h) with a 28 in roller-cone bit.

Instrumented top drive. To measure drill-string vibrations induced by the drill bit, the top drive was instrumented with two sets of three-component (3C) accelerometers (Figures 2d and 2e). The top drive rotates the drill string, and sensors are expected to measure axial, torsional, and transverse vibrations of the drill-string rig assembly (Poletto and Miranda, 2004). The cabled system from the National Institute of Oceanography and Experimental Geophysics certified for the drilling environment was utilized for real-time pilot recording and remote QC because there was no commercially available wireless system certified for hazardous areas on the drilling assembly and able to record continuously. The top drive is a congested piece of equipment, and selecting an appropriate location for the sensor in the first trial was challenging. This fact makes a compelling case for future improvement, where new instrumentation such as remote sensing can deliver vibration data from multiple locations while simplifying logistics and enhancing safety of the operation. Remote sensing also has the potential to take readings of the rotating drill string while avoiding interference with parts of vibrating surface equipment attached to the top drive (Bakulin et al., 2019a).

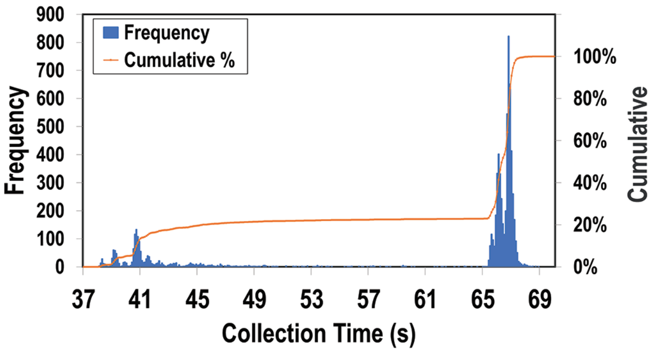

Figure 3. Histograms summarizing the wireless collection time process for a recording period of approximately 60 hours using 2750 surface stations. In less than 68 s (from the end of the trace), 100% of the data are available for real-time processing at the main recorder located on the rig.

Downhole sensor. An alternative pilot for SWD can be obtained by using downhole sensors (Poletto and Miranda, 2004). Previously, they were not readily available until the drilling community adopted 3C downhole accelerometers for monitoring vibrations of the bottomhole assembly (BHA) in order to characterize drilling dysfunctions (Greenwood, 2016). During the early days, such tools recorded so-called "burst" data (short windows of data with long silent periods). However, it has been realized that drilling dysfunctions can develop rather quickly and may occur outside the recording periods. As a result, continuous recording tools are growing in popularity. This makes sense for instrumented rigs as well as geophysical applications (Bakulin et al., 2019a). These tools use standard 1–2 ms sampling typical for seismic but often called "high-frequency recording" by drillers. Detailed tool specs are similar to SWD requirements in terms of frequency range and resolution (Poletto and Miranda, 2004).

Figures 2e–2g show placement of such a downhole tool inside a bit sub above the 28 in roller-cone bit used for one of the shallow sections. Such devices are relatively small, do not interfere with drilling operations, and can be used with any BHA and hole size.

Unlike wireless geophones and top-drive sensors, downhole tools record data in local memory, so data can be retrieved only after pulling the bit out of the hole. With the growing availability of fast EM-based telemetry, there is potential to have these data transmitted to the surface in close to real time if such information is proven superior and critical for real-time drilling decisions (Poletto et al., 2014). Here, we focus on SWD applications of the system that are obtained by using wireless surface geophones and top-drive sensors.

Preprocessing seismic data recorded using a drill-bit source

Data processing and interpretation were performed in post-drilling phase during this trial because of the prototype nature

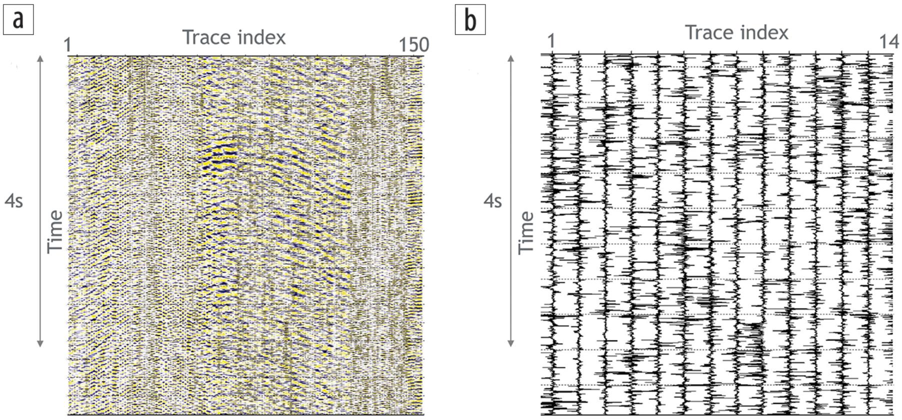

Figure 4. (a) Uncorrelated geophone data collected at the earth's surface show continuous seismic signals induced by a drill bit while drilling. (b) Drill-string vibrations as recorded by a vertical accelerometer mounted on the top drive.

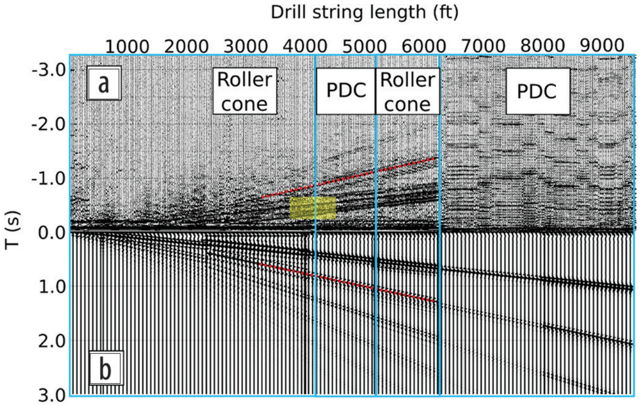

Figure 5. (a) Deconvolved field pilot traces recorded at the top drive. (b) Synthetic modeling of wave propagation in the drill string using actual BHA details.

of the DrillCAM system. The next step in real-time processing and delivery requires further development. The main goals of the processing phase are to assess the overall feasibility of the system, verify the quality of the recorded data, and pave the way to potential future applications.

The first look at a seismic gather recorded during the drilling activity clearly shows the presence of a significant amount of seismic energy generated by the working drill bit (Figure 4a). The main target signals of the SWD technique are direct arrivals and reflected waves induced by the drill bit and recorded at the surface. Since strong surface vibrations accompany the drilling process, the data are inevitably contaminated by noise that is manifested as surface waves, which are induced and radiated by the rig structure, mud shakers, engines, vehicles, generators, etc. A high level of noise requires specialized techniques and workflows for processing and interpretation of SWD data.

The first step is transformation of the continuous seismic records to standard impulse-like seismograms. To perform such a conversion, conventional SWD makes use of a pilot signal similar to the vibroseis technique. Unlike a vibroseis sweep, the drill-bit source signature is priori unknown, random, complex, highly variable, and not readily extractable from a single trace of the SWD geophone survey. In the current trial, we use the vertical component of a top-drive accelerometer sensor as an estimate of the pilot signal (Figure 4b). Autocorrelation and deconvolution of the top-drive traces and a stacking over drilling interval of 30 ft (one drill-pipe length) provide evidence of vibrations propagating along the drill string. Strong and reliable signals are seen down to 6200 ft (Figure 5). Above this depth, mostly roller-cone bits were used, with a single occurrence of a PDC bit marked in Figure 5. Below 6200 ft, only PDC bits were utilized, and they appear to induce weaker vibrations in the drill-string pipes that do not propagate over large distances. Dipping events in Figure 5 correspond to multiples bouncing between the borehole assembly and the top drive. These multiple arrivals are typically used to estimate drill-string propagation velocity and time delays required to redatum the pilot time from the top drive to the subsurface bit location. By using the actual BHA and drill-pipe configurations, synthetic modeling of the extensional waves in the drill string is performed for top-drive location. We observe a consistent match between the real and synthetic data, verifying the reliable quality of the recorded pilot and overall functionality of the top-drive recording system.

Correlation and deconvolution of pilot traces applied to the surface geophone data (Poletto et al., 2001), followed by vertical stacking over a 30 ft depth interval, provide conventional common-shot seismograms with a source position corresponding to the current drill-bit depth. An example of such a gather shows a direct-arrival event overlaid by powerful and coherent noise (Figure 6a). This noise is typical for SWD surveys and may be caused by rig noise or by drill-bit vibrations propagating along the drill string and inducing refracted and surface waves that propagate away from the rig as a conversion point (Figure 6b).

The dominant frequency of this noise is typically low compared to primary events. High-pass filtering is effective for reducing it to some extent. Poletto and Miranda (2004) show that, by construction, this noise is typically stationary versus bit deepening and can be discriminated in the common-receiver domain. Additional stacking of several receiver lines in the crossline direction enhances the signal and provides common-shot seismograms (Figure 7) that are typical for SWD land surveys. Direct arrivals are clearly identified and can be used for velocity estimation between the bit location and the surface, while observed deeper reflections can be used for imaging purposes and look-ahead prediction. After resorting all common-shot gathers into the common-receiver domain, we extract a reverse vertical seismic profiling (VSP) gather (Figure 8a). We note the poor signal-to-noise ratio typical for single-sensor measurements in a desert environment with complex near surface that usually requires aggressive enhancement (Bakulin et al., 2019b). As such, future surveys may benefit from large receiver arrays of several tens of meters (Poletto and Miranda, 2004), which is typical for conventional SWD surveys, even in less-complicated near-surface conditions. The application of supergrouping (Bakulin et al., 2018) with a group size of 100 × 100 m provides dramatic signal enhancement, uncovering drill-bit signal from the carpet of scattered noise. The final reverse VSP gather, with an offset of 475 m from the well (Figure 8b), resembles conventional VSP gathers and contains major seismic events such as direct wave, reflected, and converted arrivals.

SWD applications

Since wireless geophones stream data from the entire seismic spread to the central rig recorder in close to real time, automating land processing flow on a rig computer instantly delivers seismic gathers that are ready for various SWD applications. We illustrate and discuss several potential applications of the system by using the recorded data. Some of the applications are intended to provide real-time information to improve drilling decision making. Others enable obtaining additional valuable information for exploration, which is not readily available from the current practices and toolkits.

Check-shot while drilling. As the first application of this integrated SWD system, we describe retrieving a

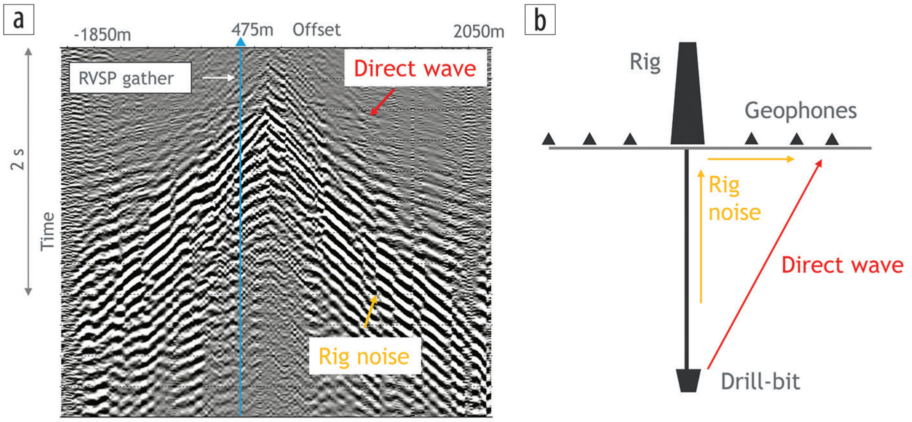

Figure 6. (a) Common-shot gather for bit depth of 4000 ft after deconvolution shows direct arrivals and rig noise. (b) A schematic of the propagation path of the rig noise component induced by the bit.

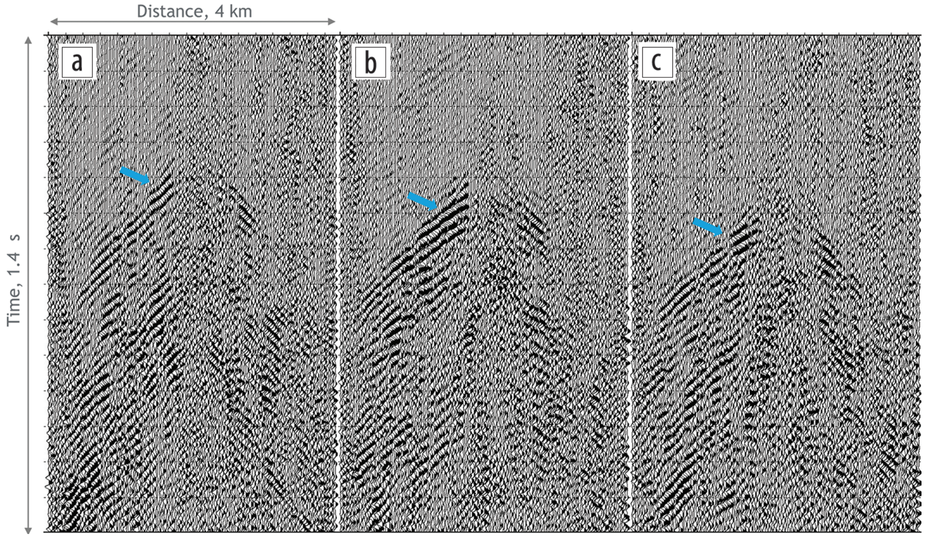

Figure 7. After stacking several receiver lines and high-pass filtering, common-shot gathers for each bit position show distinct direct-arrival events marked by arrows. (a) Bit depth of 3690 ft. (b) Bit depth of 4590 ft. (c) Bit depth of 5640 ft.

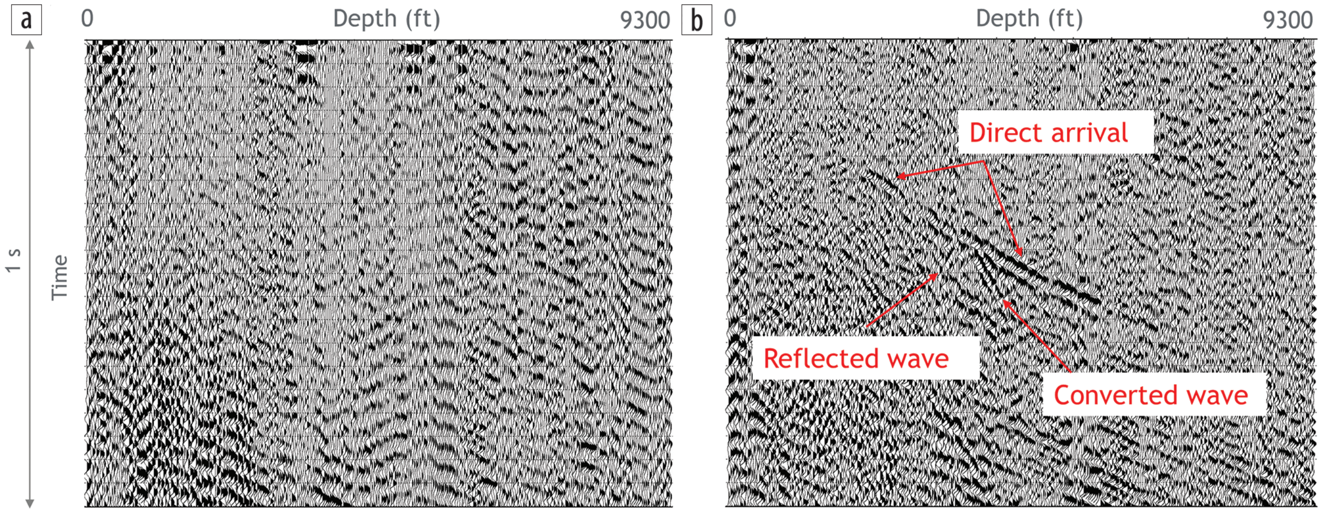

Figure 8. Single-sensor reverse VSP gather at an offset of 475 m (a) before and (b) after preprocessing using supergrouping of 25 adjacent traces. Observe clear VSP arrivals on (b) but not on (a) due to intense scattered noise in the near surface.

time-depth curve or so-called "check-shot while drilling" (Miranda et al., 1996). The conventional check-shot survey is performed by inducing seismic waves at the surface and recording them down the hole by using seismic sensors clamped to the borehole wall. A wireline check-shot survey consumes rig time and requires well intervention and mobilization of a VSP crew to the rig. It is only available after drilling, and hence addresses postdrill time-depth seismic conversion, interpretation, and assisting future prospects. With a check shot obtained while drilling, time-depth relation can be recalibrated in real time, whereas the bit can be accurately located on the seismic image, even in the presence of significant errors in the depth velocity model. Real-time check shot helps reduce predrilling depth uncertainty for key formations and enables a more accurate selection of casing points for drilling. As mentioned earlier, borehole geophysics in cased holes often struggles to deliver conventional check shot in shallow sections of the well. From an exploration perspective, this prevents us from addressing substantial uncertainty associated with velocity variations in the complex near surface and shallow overburden typical of arid environments. The SWD check shot has the potential to provide the required time-depth information along the whole depth interval starting from the surface, thus mitigating this significant uncertainty. While the described survey utilizes reverse VSP data recorded at the surface with a drill bit as a seismic source, a check shot while drilling can also be obtained by using a conventional surface source and downhole receivers (e.g., Esmersoy et al., 2005).

After the preprocessing stage, we obtain a reverse VSP gather at an offset of 475 m and pick first arrivals (Figure 9) following conventional VSP analysis. The data quality allows us to obtain reliable picks in the depth interval of 1830–7290 ft. It is interesting to note that while intervals of 4200–5200 ft and 6200–7300 ft were drilled with PDC bits, they possess good data quality similar to other intervals drilled with roller-cone bits. However, below 7300 ft (PDC bits only), arrivals become hard to pick when using conventional methods. Since no wireline VSP was available in the considered well, to validate the obtained check shot, we construct a composite synthetic model by using surveys from three nearby wells. A modeled VSP gather shows good correspondence with the real gather in terms of direct arrivals (Figures 9a and 9b). The picked traveltimes for SWD after the verticalization step (transforming picked times from offset to zero-offset measurements) show a good match with the check-shot profile from a nearby well obtained by using conventional VSP acquisition (Figure 9c). The variation is mainly due to the first-break jittering effect noted on the noisy field gathers. Validation confirms the ability of the SWD acquisition system to deliver a reliable time-depth curve along the extended depth interval, similar to conventional VSP surveys. We note that the shallow time-depth information is not readily available from the considered reverse VSP gather due to its finite offset. Data with smaller offsets have stronger contamination by rig noise, requiring more advanced techniques and multiple neighboring receivers to address. We conclude that the presented example clearly illustrates the availability of reliable time-depth information in the SWD data recorded in real time.

Ahead-of-the-bit prediction. While check shot only relies on direct arrivals and allows the instant location of bit on seismic, a more advanced SWD application is to use reflected arrivals to look ahead of the bit, specifically to predict key upcoming formations and overpressure zones while drilling. In flat geology, a typical drilling program relies on the estimated formation depths derived from adjacent wells or from seismic. In the presence of a complex near surface, uncertainties in these estimations can reach hundreds of feet, adding additional risk and cost to the drilling operations. The SWD provides effective means to refine the estimate of the formation depths ahead of the bit. SWD accuracy improves with decreasing distance to the target, making it an ideal method to tackle uncertainty in overburden horizons.

To illustrate this process, we further process zero-offset synthetic and real finite-offset VSP data sets to enhance the upgoing reflection arrivals. Figure 10 shows both after two-way-time (TWT) flattening and median filtering, which enhances upgoing waves. Reflection events associated with already drilled and ahead-of-the-bit formations are observable both in the field and in synthetic data. The field gather after unflattening is plotted in Figure 11. The marked reflector is an interface that is associated with an expected overpressured zone known from offset wells in the area. Accurate depth prediction is critical for mitigating drilling hazards and for the precise setting of the casing point. The predrilling depth estimate was 10,047 ft. By using a reverse VSP gather, we show how more accurate look-ahead prediction can be achieved. Kinematic extrapolation of the reflector in time and depth is performed below the current drill-bit depth location. Similar to this, the picked check-shot traveltime curve is extrapolated by using the existing velocity trend from nearby wells. The intersection of these two lines provides

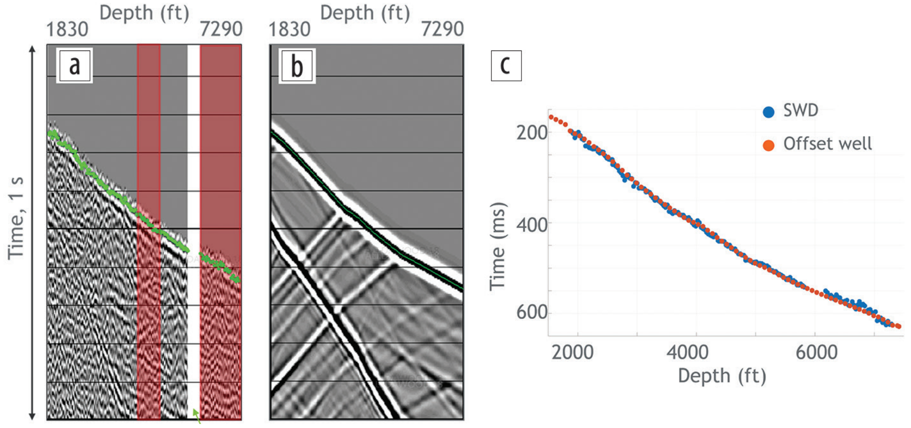

Figure 9. Comparison between (a) real and (b) synthetic reverse VSP gathers at an offset of 475 m from the rig shows good match between direct arrivals. The red rectangles denote sections drilled with PDC bits. Green dots denote picked first-arrival traveltimes. (c) Picked SWD traveltimes after verticalization (blue dots) show good match with conventional VSP check shot (red dots) from a nearby well.

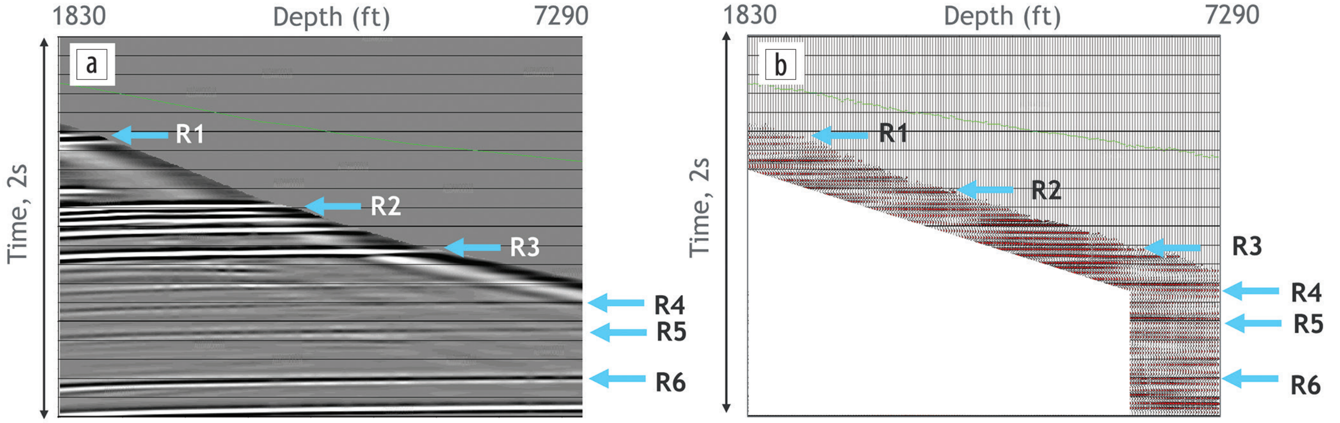

Figure 10. (a) Zero-offset VSP synthetic and (b) a reverse VSP gather after enhancing upgoing reflections and TWT flattening. Observe reasonable correlation between the key reflectors marked by arrows above and below the bit at a depth of 7290 ft.

an improved look-ahead estimation of 9930 ft, with some uncertainty caused by extrapolation and picking errors. The actual formation top was penetrated at 9920 ft, confirming the accuracy of kinematic prediction when the bit was 2640 ft away from the formation. The prediction accuracy improves as the bit gets closer to the formation due to reduced velocity error ahead of the bit. Kinematic prediction illustrates the value and potential of the SWD data for the accurate location of key formation tops ahead of the bit in real time. More advanced imaging-based techniques utilizing extended wireless recordings over the surrounding area can also be used to improve such prediction and to locate the reflector away from the well.

Corridor stack from SWD data. As the last step, following conventional VSP processing, we generated a narrow corridor stack around the first breaks from the TWT-flattened gather in Figure 10. We inserted it into the surface-seismic time-migrated section (Figure 12). We observe good correlation between the surface seismic and the VSP corridor stack and a notable tie of key reflection events. This tie further validates that the acquisition system provides reliable, good-quality data in terms of direct arrivals and reflection events. The comparison identifies a time window on surface seismic with potential multiples contamination that may typically occur in this region. Such a mismatch is useful for tuning seismic processing workflows that struggle to reliably suppress surface and interbed multiples. Considering that a significant number of new wells are drilled every year, equipping them with such a seismic acquisition system may provide additional valuable information that can be used for reprocessing of conventional surface seismic and better calibration of velocity models for future exploration, often targeting deeper or subtler structures in the same areas.

Conclusions

We have conducted a successful trial of the SWD system with wireless geophones at an onshore well, delivering a complete data set of multiple continuous measurements from the surface down to 10,000 ft. Despite challenging near-surface conditions, generally hard rocks and large-diameter bits are expected to be favorable for SWD applications. Three main acquisition components consisting of surface geophones, top-drive sensors, and downhole accelerometers were integrated for the first time by using existing and novel elements. Specifically, we evaluated wireless geophones and proved that they can reliably deliver large volumes of data in close to real time for different applications. The use of wireless stations allowed sensor placement within the rig pad in areas crowded with equipment where cabled systems would not have been viable. Also, the wireless system enabled the use of flexible and adaptable surface acquisition geometries with apertures that increase with depth to optimize SWD. A continuously recording 3C downhole accelerometer was tested, and it delivered reliable data with submillisecond sampling. These data were utilized to estimate formation properties and to identify drilling dysfunctions. Continuous recording of all data and completeness of the data set (0–10,000 ft) make it a perfect candidate for various analysis techniques based on artificial intelligence.

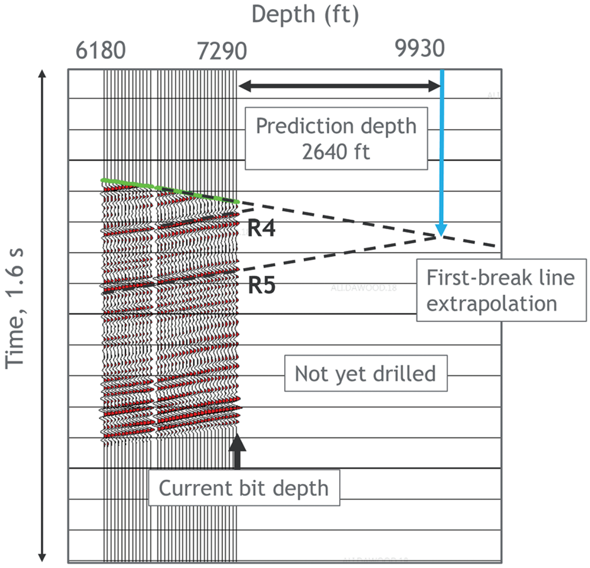

Figure 11. Look-ahead kinematic prediction. The unflattened field gather from Figure 10 is kinematically extrapolated to accurately predict the depth of the key R5 reflector. Depth is estimated at 2640 ft ahead of bit or 9930 ft total depth. This estimated depth shows good match compared with the postdrill formation top picked at 9920 ft.

By using specialized land processing, including supergrouping, we successfully transformed the drill-bit recordings into reliable seismic signals that are ideal for various SWD applications. We specifically demonstrated real-time while drilling check shot and validated results by using nearby wells. We showcased successful look-ahead prediction by using VSP reflections, significantly reducing predrill uncertainty. Finally, we obtained good ties between SWD corridor stack and surface seismic. Most processing steps can be easily automated, allowing continuous data processing and interpretation that will facilitate drilling automation and improve real-time decision making.

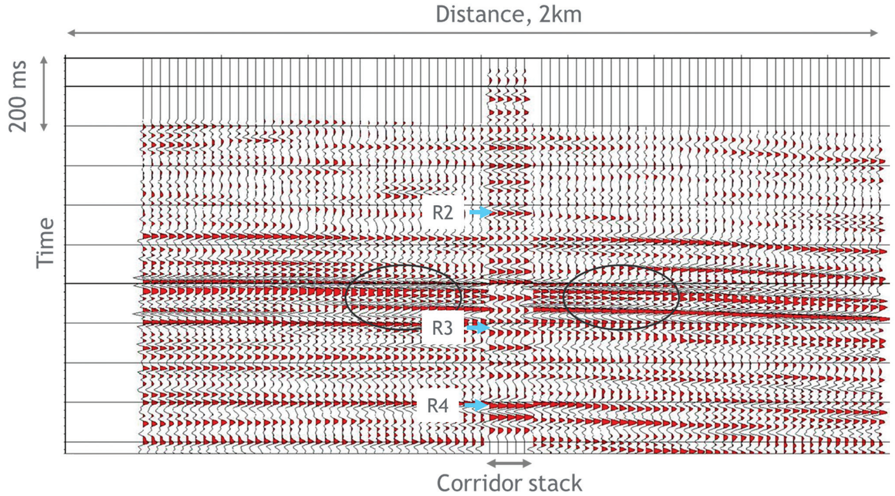

Figure 12. A zero-offset VSP corridor stack from the SWD data is spliced into a surface seismic section. Observe good tie with key formation tops after their depth-to-time conversion using the obtained SWD check shot. The corridor stack also ties nicely with the time-migrated image. It helps to identify intervals (marked by circles), where unsuppressed multiples can cause interference and break the tie with VSP data.

Future experiments may benefit from larger geophone arrays instead of signal sensors. The lack of accurate time synchronization was identified as a significant barrier for easy integration of downhole near-bit pilot recording into processing. As for processing and analysis, future studies will focus on extending the check-shot curve to the shallower and deeper intervals by using more advanced 3D processing and imaging ahead of the bit using an extended multioffset SWD VSP data set.

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Data and materials availability

Data associated with this research are confidential and cannot be released.

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