# A review of seismic-while-drilling technique: from 1986 to 2020

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## ABSTRACT

Seismic-while-drilling (SWD) is a technique that explicitly creates an array of sources together with the progression of drill bit towards deeper layers. It provides great potential in energy industries, and surveying geophone arrays can receive the signals from underground, thus providing additional information. In the past few decades (1986-2020), the industry and researchers systematically realized many advantages of SWD and made it a merging project. SWD is often acknowledged as a promising auxiliary tool in exploration geophysics since the additional ray paths generated from the subsurface can complement current seismic exploration approaches, which need a relatively comprehensive acquisition. For example, Full-Waveform-Inversion and migration. However, this technique still needs to be further exploited before being widely utilized. This paper aims to summarize the basic principles of SWD and review the progress, mainly focusing on its practical applications in exploration seismic from the 1980s to recent for supporting future development directions.


## INTRODUCTION

Seismic measurements play a crucial role in geophysical exploration and geological interpretation. Surface reflection seismic is one of the most widely used tools. By analyzing the 2D or 3D surface seismic sections, interpreters will obtain the necessary information of target areas, which is helpful for the determination of drilling locations and geological interpretation. However, the lack of illumination in surface seismic may arise significant uncertainties in this phase (Kazemi et al., 2018). To reduce this type of uncertainty, conventional vertical seismic profiles (VSP) where the receivers are downhole is applied to correlate the data of surface seismic lines with the well-log data during or after drilling (Poletto and Miranda, 2004). Indeed, this approach offers a better resolution but implies high costs as well as risks.

On the one hand, if multiple pairs of borehole receivers and shot offset positions are needed, the standby time of drilling equipment should increase, drastically raising the cost. On the other hand, severe consequences such as a blow-out may occur if there is no effective control for pressure after the drill is off the well. Seismic-while-drilling has been introduced these years to rectify such limitations. SWD does not need the installation of downhole instruments, which is beneficial for controlling the cost. Moreover, this technique is applied simultaneously with drilling operations and does not interrupt it, meanwhile generating a collection of extra seismic information in real-time or depth measurements after processing. Since SWD can be regarded as an inverse or reciprocal of VSP, extending the surveys to distant locations can be realized by adding more seismometers to the surface seismic sections.

The idea to use drill-bit sources appeared way back in 1930. However, researchers began to monitor and study the vibrations from the drill bits extensively and produce reliable geophysical results since the 1980s. Initially, drill-string vibrations were investigated to determine the bit position while drilling and monitor the drilling process. Klaveness (Klaveness, 1980) installed a pulse signal generator near the string and used surface receivers to estimate drilling direction and lithology. Another method used bit-generated coherent acoustic signals received by near-well geophones to get a relatively precise bit position (Katz, 1984). Elf-Aquitaine filed for a patent that measures the time shift between the top-of-drillstring and a surface receiver using crosscorrelation (Staron et al., 1988). Because this patent was firstly filed in 1986 in the UK and inspired many researchers in exploration geophysics, this paper mainly reviews the SWD technique from this year.

Various approaches have been considered successful in explaining the source mechanism or improving the conventional seismic to investigate subsurface features. In particular, after filing the initial Elf patent, Rector and Marion (J. W. Rector and Marion, 1991) published a promising result by matching, grouping, correlating, and stacking the data from the top end of a drill pipe and receivers placed on the surface a representative of acoustic waves can be produced. The travel times can be read from the profiles. From then on, the first SWD commercial under the license of TOMEX$^{\mathrm{TM}}$ was developed and began to offer relating services. In the same period, some researches aimed to characterize the radiation pattern of bit sources was carried out. Rector and Hardage (James W. Rector and Hardage, 1992a) studied the wavefields generated by roller-cone bits; Widrow (Widrow, 1990) applied adaptive filters to extract the drill-bit signature and calculate the corresponding reflections; Angeleri et al. (Angeleri et al., 1996) developed a method that can separate pilot signals from noisy traces. Based on these works, deeper understandings of SWD came out. Poletto et al. (Poletto et al., 2005) demonstrated how different the drill-bit multiples were, and this was a possible reason for an incorrect deconvolution when processing SWD signals. Richard et al. (Richard et al., 2004), Germay et al. (Germay et al., 2009) and Boussaada et al (Boussaada et al., 2012) paid attention to the boundary conditions in the representation of drill-bit sources and discussed them based on different rock properties. More possible applications for different situations were also discussed. In seismic imaging, SWD was verified by synthetic models and numerical experiments. Kazemi et al. (Kazemi and Sacchi, 2014) first applied the multichannel sparse blind deconvolution (SMBD) algorithm to provide a drill bit-rock signature, and then combined the migrated the SWD data with the surface seismic image to improve the illumination (Kazemi et al., 2018), their results showed the feasibility of using the variability of seismic source positions in migration. In 2020, they developed a modeling and estimation framework for the drill bit source signature and applied this technique to the successive Full-Waveform-Inversion (Kazemi et al., 2020). Their sequential inversion method was able to recover the deeper section of the model.

The central structure of this paper is about the basic introduction of the Seismic-while-drilling method. It mainly includes what radiation patterns the source has, what acquisition systems does is require, and what we can do with SWD datasets, together with some representative examples in the period mentioned in this paper.

## Description of the seismic-while-drillng method

As mentioned in the previous part, the Seismic-while-drilling has been applied and explored as a tool in many contexts. Although researchers used different approaches in the data correlation part in some cases, the basic principles of SWD are universal. This part is about the basic ideas of the SWD technique.

### *Radiation patterns*

There are several kinds of drill-string models, here consider a vertical well for simplicity. As shown in Figure 1, a drilling set usually contains a rotary table, a drill string, and a drill bit. The rotary table produces rotary motion and motivates the dill-string to rotate around its central axis at a constant spinning speed $\omega_0$ and a constant penetration rate $V_0$. The drill string is a combination of flexible tubes with distributed stiffness and inertia properties. There is a drill collar made with heavy section, and it connects the drill bit with fixed blades. According to a laboratory experiment in 1988 (Sheppard and Lesage, 1988), axial and transverse impacts occur simultaneously, and the latter create symmetrically distributed force couples at the bottom in each rotation. Therefore, as a roller cone bit keeps going down the underground layers and destroying the rock at the bottom, an axial vibration is generated. The corresponding energy is equivalent but opposite in the forward direction and radiates in compressional or transverse waves to the formation (Kapitaniak et al., 2015), which means the drill-bit can be a dipole source for P-, SV-, and SH-waves. This kind of source can radiate acoustic and elastic energy to the fomation (James W. Rector and Hardage, 1992b; Meehan et al., 1998). However, the power of SH impulses is much less than it of P and SV ones, since the SH amplitude is produced by a weaker force couple, and is theoretically scaled by a frequency-dependent factor (James W. Rector, 2005). Figure 2 depicts the radiation pattern of a vertical drill string in an isotropic and homogeneous formation in which the layers are horizontally piled, and it can be observed that there are feasible signals can be used in surface seismic. The amplitudes are de-factored, and the radiation patterns are estimated under atmospheric conditions. For the signals received by seismometers deployed directly above or near the borehole, the only contributor is from P-waves; for signals recorded on larger offset, SV- and SH- waves begin to get involved. Besides, there are several noise sources shown in this figure. The green arrows represent for the head wave ray paths generated by head wave emanation points in drill string (green dots in Figure 2), and the red water level lines show there is radiation of energy from drilling rig into earth.

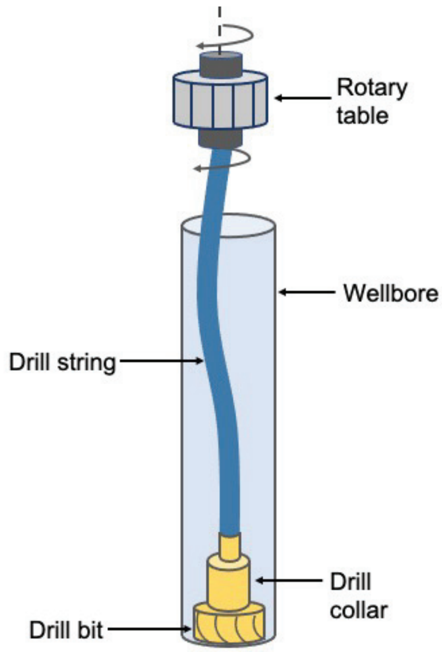


FIG. 1. Typical drilling set

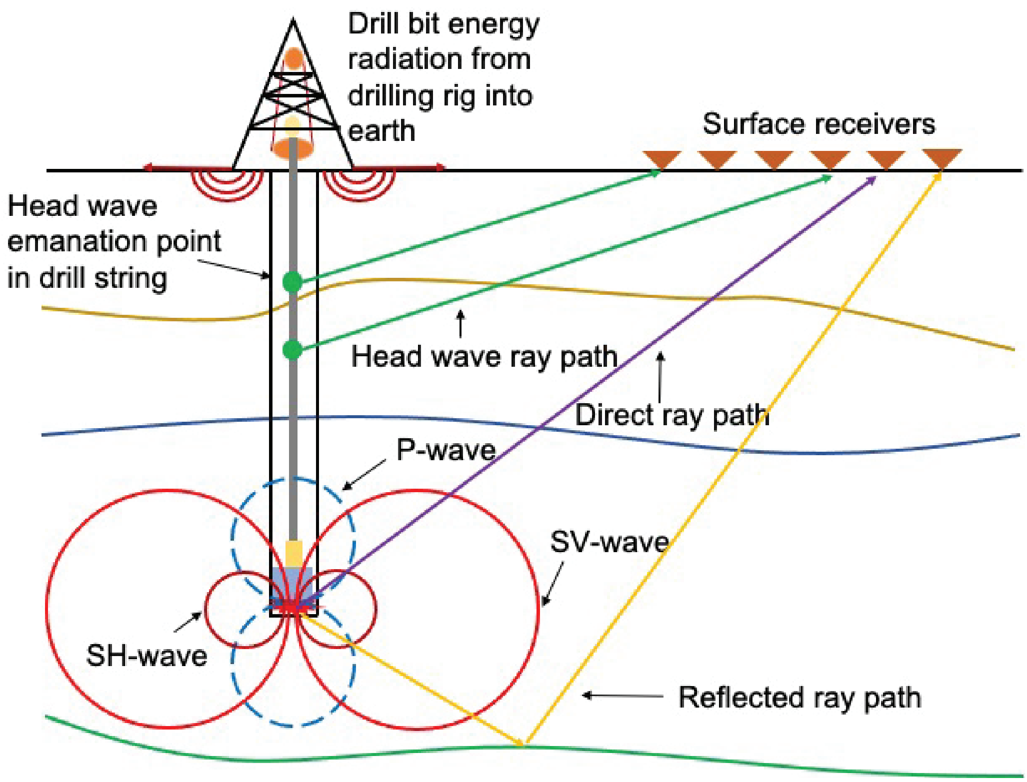


FIG. 2. Seismic-while-drilling radiation patterns in the vertical well

*Acquisition system*

The layout of seismic lines is guided by the exploration requirements, theoretical radiation patterns, and noise impacts.

Seismic lines usually lay down near the well and are aligned with the dip direction of the geological structure to get rid of extra work in preprocessing. Generally, the lines can be long enough to be several kilometers with variable or fixed spacing. According to Yilmaz (Yilmaz et al., 2001), the resolution in velocity analysis positively correlates with the length of seismic lines. This feature is essential when calculating the move-out of direct waves and analyzing the velocity spectra, especially for deep reflections. The other optimistic quality of large spread is the ability to discern nose signals. When a seismic line extends at several hundred meters or some kilometers, it is usually easier to discriminate valuable signal and noise using their move-out variation with offset or depth. The foundation is the stationary feature of some noise, which means this kind of noise has the same delay at different drill bit depths. A larger offset means more combinations of offset channels that enable multiple coverages which are beneficial in indoor processing. Another progressive nature of large channel numbers is the availability of feasible common-source and common-receiver gathers. When provided a comprehensive set of data including enough information from common-source and common-receiver domains, the analysis of data can be much more effective. Figure 3 shows an adaptable acquisition geometries increasing aperture with bit depth (Bakulin et al., 2020). The central red dot is the drilling spot. The blue dots denote receiver positions for drilling from the surface to 2600 ft, and cover a smaller aperture with denser sampling. The orange dots are the receiver arrangement for recording signals while drilling in deeper sections with a larger layout and sparser sampling by using the same number of sensors.

Radiation patterns of SWD sources also guide the acquisition system. As mentioned in the previous part, assuming the drill string is vertical, the roller-cone bit source can generate compressional and shear waves whose energy is proportional to the angle between bit depths and channel location. The intensity of P- and S-waves concerning bit depths has an opposite correlation with offset. Quantitively, in a Poisson medium, the radiation power of P-waves is around ten percent of the total energy of P- and SV-waves, and it is thirty percent of the total along the drill string. For the horizontally polarized waves, the radiation pattern is similar to that of SV-waves. This component is also detectable in the SWD acquisition system using three-component geophones. In the assumption of vertical drilling, shear waves can be easier received at a relatively larger offset. Therefore, if the exploration aims to utilize P-waves, it is reasonable to apply denser sensors to the line; if the information of S-waves needs to be extracted, a larger offset is necessary. Moreover, it is reasonable to use a shorter array at larger offsets because the apparent velocity of S-wave is lower.

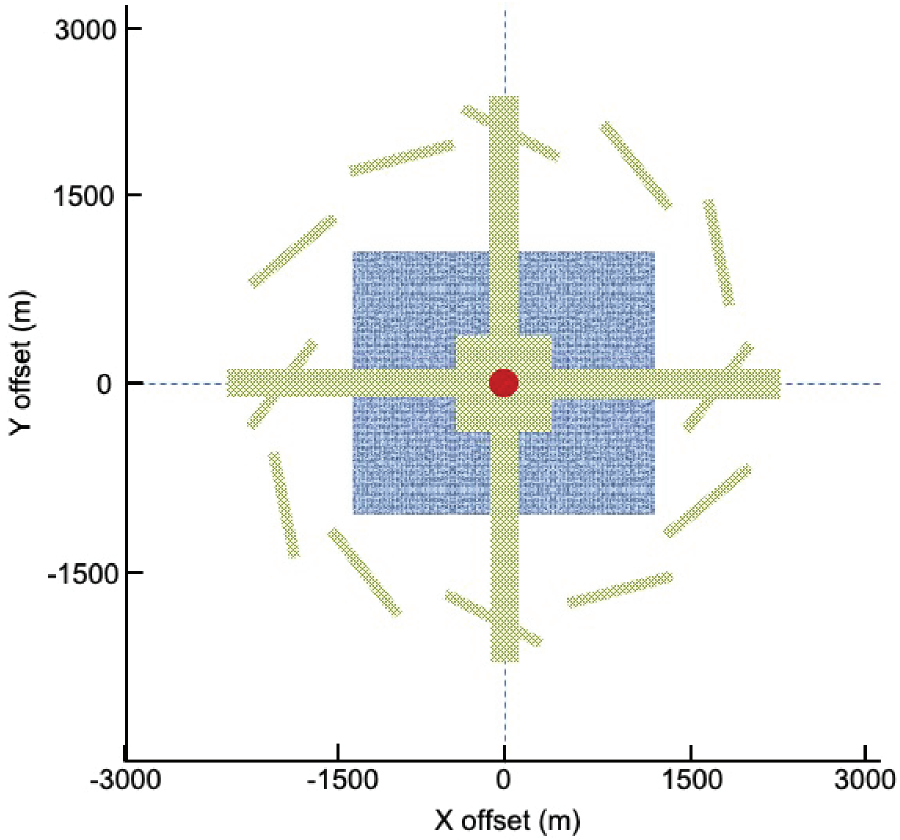


FIG. 3. An adaptable acquisition system

Noise can have significant impacts on data quality and plays a negative role in the processing. In general, the data in the SWD method is measured by a several-minute time interval, which makes it integrated with coherent noise from drilling activity. Besides, data will be mixed with ambient noise due to the scattering effect from random-noise sources near the surface in the proximity of the lines. There are mainly several noise types: surface waves generated by rig vibrations in the well area, strong coherent signals generated from deviated drilling, pure and scattered random noise. These kinds of noise may also be strengthened at a different rate in SWD data processing because of the correlation process. It is possible to filter away some noise (rig vibrations) using signal processing approaches such as filtering, but some signals may also be rejected. Therefore, it is essential to select optimum receiver arrays to spatially suppress the coherent and ambient noise and maximize the signal-to-noise ratio.

Assuming that all the receivers in a linear array have the same sensitivity, ground-coupling, and directivity properties (Aldridge, 1989), the analysis of array response to noise can be carried out (Levin, 1989; Poletto and Miranda, 2004). Theoretically, an array is determined by the number of receivers $N$ and the length $L$. These two parameters also influence the signal-to-noise ratio either for coherent noise or for random noise. In general, a larger number of $N$ is necessary to prevent the data from being degraded by scattered random noise. At the same time, the selection of $L$ depends on the portion of random and coherent noise because they have different effects. As a general guideline, the typical condition for the SWD method can generate low-frequency coherent noise. It is preferred to use more extended arrays; shorter ones can better suppress noise when random noise dominates.

*Applications of SWD*

There are many projects can be carried out with seismic-while-drilling system. Generally, it can be summarized into five types according to different conditions and demands.

1. First arrival time of the compressional waves

This product is also called "check shot," It is usually the first step in most integrated SWD systems. Check shot infers the retrieving of a time-depth curve that conveys the direct P-waves' travel time from the bit to near-offset geophones (Miranda et al., 1996). Conventionally, this is performed through surface seismic and VSP. By inducing seismic waves from the surface and recording them with sensors attached to the borehole wall, the travel time of first arrivals can be estimated. However, this can only be applied after the drilling process, which means there are both demands of higher cost and potential risks. With the help of Check shot-While-Drilling, the time-depth relationship can be converted to real-time because it is direct to receive signals from the correct positions of a drill bit. Therefore, the bit can be located more accurately. It is also possible to eliminate errors in the estimated depth-velocity model because of the calibration of travel time (Esmersoy et al., 2005). Check shot carried out with SWD helps reduce the uncertainty in monitoring drilling depth and enables more flexibility to the drilling process. Specifically, suppose the near-surface structure is complex. In that case, an SWD check shot can prevent researchers from addressing uncertainties raised from the great velocity variation because of the ability to offer the time-depth information along with the whole depth interval.

One of the key steps in check shot is verticalization. This process means correcting the first break travel time of near-offset traces to the arrival time of vertical travel path. As shown in Figure 4, for small offsets, there is an approximation of the relationship between zero-offset and near-offset travel time:

$$t_0 = t_{fb} \cos\theta, \tag{1}$$

where $t_{fb}$ is the first-break travel time received by near-offset sensors, and

$$\theta = \arctan\frac{X}{Z} \tag{2}$$

In equation 2, X is the offset and Z is the depth of the bit. The approximation in equation 1 is only available for $\frac{X}{Z} < 0.2$. The verticalization process here can also be regarded as surface static correction. The two-way travel time on the datum plane:

$$t = 2(t_0 + t_s), \tag{3}$$

where $t_s$ is the seismic-datum time.

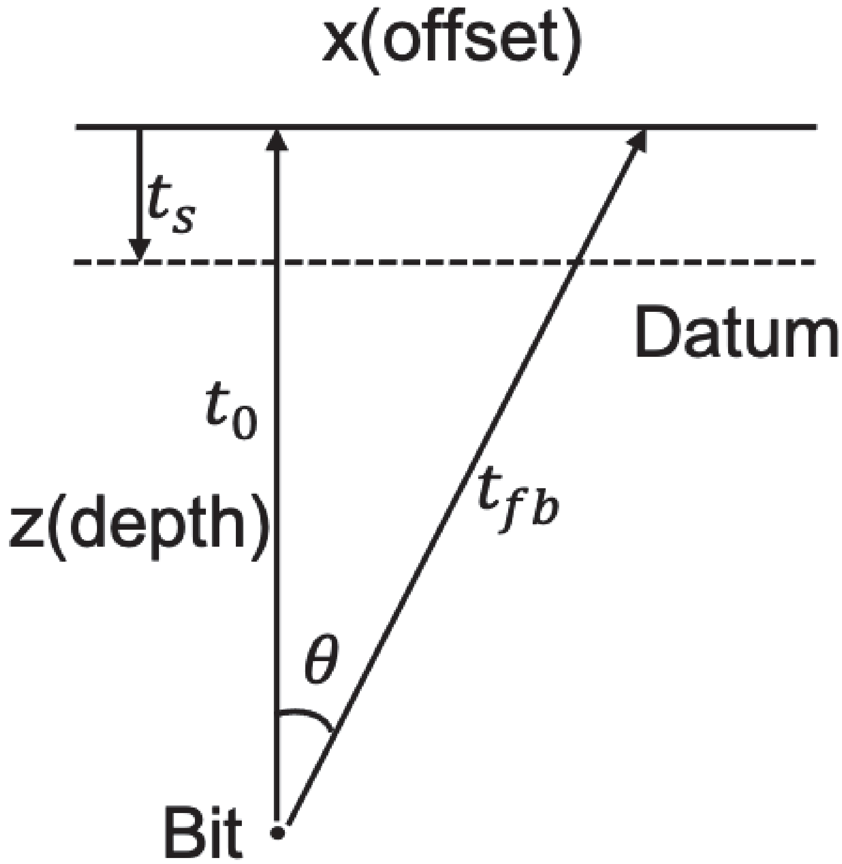


FIG. 4. An adaptable acquisition system

2. Ahead of the bit predition

This is a more advanced SWD product since it uses reflection information via multi-offset processing to predict overpressure zones or key objectives. In a complex near-surface condition, the drilling program will be significantly influenced by the uncertainties. The SWD can effectively predict the upcoming formations because accuracy is higher when the bit reaches targets. One of the requirements of ahead-of-the-bit is being finely preprocessed so that the signal-to-noise ratio will be relatively higher. Moreover, SWD data should have repeatability and a sufficient number of recorded depth levels for separating the wavefields.

Because in this application, direct arrival and multiples (as upgoing wavefields) and reflections (as downgoing wavefields) will be extracted and separated. The latter wavefield, particularly the primary reflections, is used to predict a horizon below the bit.

A reverse vertical seismic profile (RVSP) exploration implemented by Polletto et al. (Poletto et al., 2003) utilizes 3D RVSP and multi-offset 2D VSP CDP mapping in the prediction of geological interface ahead of the bit. The location of this fieldwork is Sicily, Italy. The results show some helpful information for a well-planned drilling execution and a better geological interpretation. At a depth of 2610 meters, the penetration rate is slower because of hard quartz sandstone. This unexpected layer is predicted by the 3D while-drilling migration at a bit depth of 2442 meters. Figure. 5 shows a 2D section extracted by the 3D migrated while-drilling data at a bit depth of 2442 meters. This section shows the top and bottom of this layer by "T" and "B," respectively. Besides, the 3D migrated data shows an evident reflection at a depth of 2980 meters (Figure. 6), and the sonic log acquired at the end of the drilling program indicated an abrupt decrease of compressional velocity. This sudden change corresponds to a high porosity zone with gas.

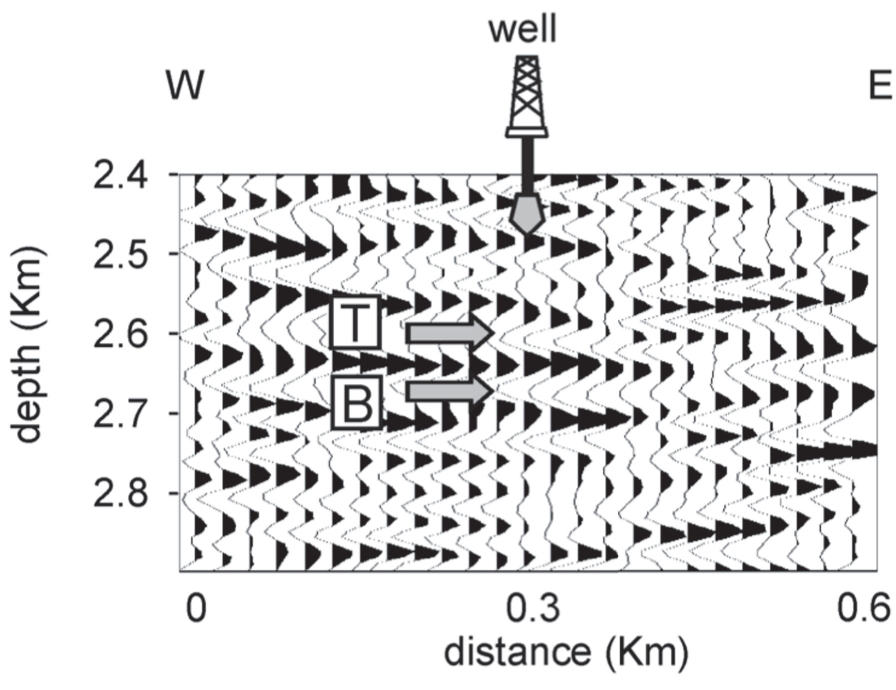


FIG. 5. A 2D section extracted by the SWD migrated cube shows the top (T) and the bottom (B) of the hard quartz sandstone layer. (from Polletto et al., 2003)

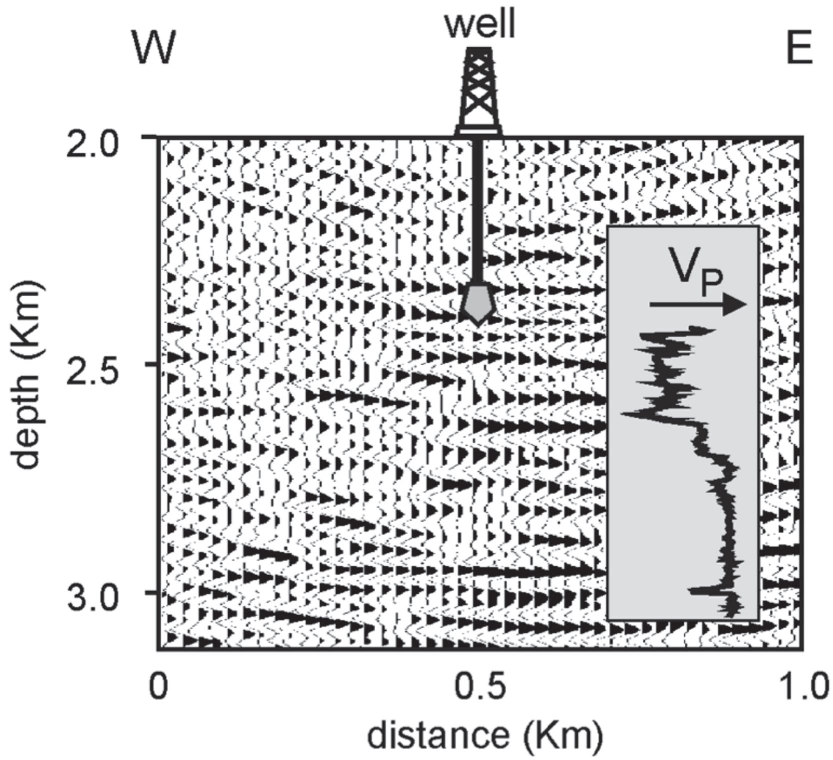


FIG. 6. Prevision with SWD migrated data of 2442-m. Depth image is compared with P-velocity function obtained by sonic log. (from Polletto et al., 2003)

Figure 7 and Figure 8 (Bakulin et al., 2020) show an example of this process. The left figure in Figure 7 denotes a zero-offset VSP synthetic data. At the same time, the right one is a reverse VSP gather after enhancing upgoing reflections by two-way-time flattening and median filtering. Reflection events can be observed in synthetic and field data, and the already drilled reflectors (R1-R6 marked by blue arrows) show a reasonable correlation. The layer after R6 implies that the ahead-of-the-bit formation can also be observed. The green lines are first arrivals. Figure 8 shows the kinematic prediction after unflattening the data. The marked reflector is related to a risky zone where the overpressure happens in a high possibility estimated from prior information. The provisioned drilling depth is 10,047ft, while the kinematically extrapolated R5 reflector predicts the total depth should be 9930. This estimated depth is then verified with the post-drill formation top picked at 9920ft.

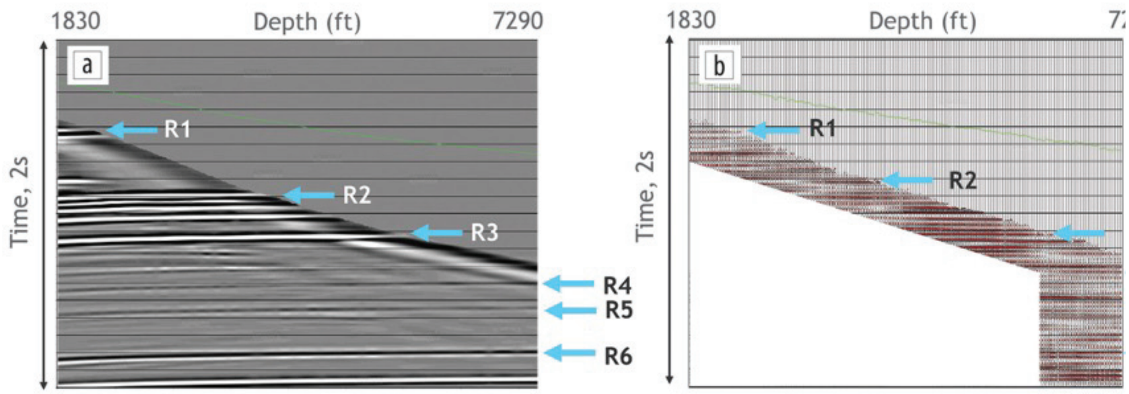


FIG. 7. Ahead-of-the-bit prediction. (from Bakulin et al., 2020)

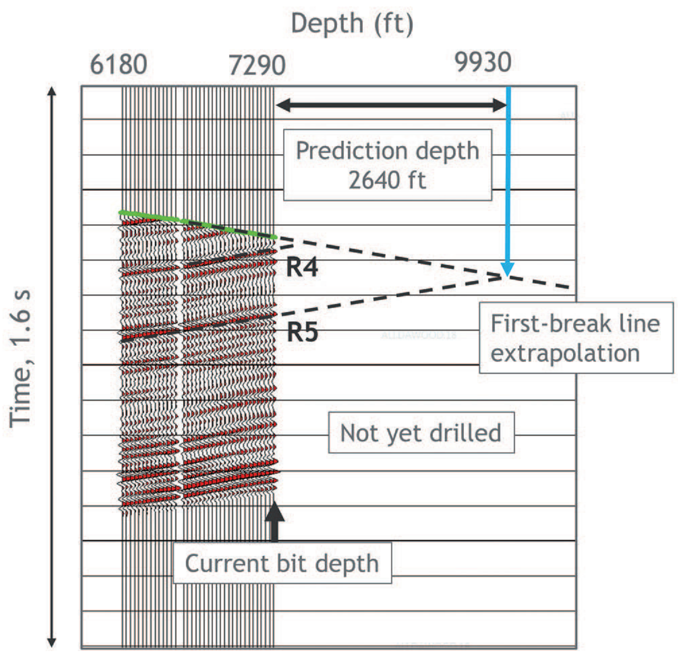


FIG. 8. Ahead-of-the-bit prediction. (from Bakulin et al., 2020)

3. Seismic imaging

Since SWD can provide the extra lateral dataset, it is promising to complement the lack of illumination in conventional surface reflection seismic. Bertelli and di Cesare (Bertelli and di Cesare, 1999) first proposed using the velocity information from the real-time reprocessing of the while-drilling dataset to make adjustments to the initial geophysical model and continuously refine it. Specifically, given a set of field data of poor quality, the depth section can be better migrated iteratively with an updated velocity model derived from SWD measurements. This idea can be realized for the purpose of making operational decisions during the drilling program. Recently, such a train of thought also inspired new projects in seismic imaging.

Kazemi et al. (Kazemi et al., 2018) bring an opportunity to address the seismic illumination issue by conducting a feasibility study of combining the SWD to surface seismic imaging. They initially apply a sparse multichannel blind deconvolution (SMBD) algorithm (Kazemi and Sacchi, 2014) to simulate the SWD source signature, which will be used for imaging from the SWD dataset. After finishing the surface imaging, they merge the SWD and seismic imaging results to improve the migrated section's sensitive improvement. Figure 9 is the acquisition system and the Sigsbee2a model in their work. For simulation of deeper sources, the bit-rock interaction is considered source signature, and the second-order acoustic finite-difference is used as an engine. Receivers are near the surface with an offset of 9 kilometers from the well location. After estimating the source signature used in the pre-stack reverse time migration algorithm, subsurface reflectors can be successfully imaged. As shown in Figure 10, the deeper part of the salt region (within the blue rectangle) can be recovered when the extra data from SWD is fed. At the same time, surface seismic imaging fails to address the illumination problem. This research has shown that the SWD dataset can help as a complementary part in seismic imaging with synthetic data.

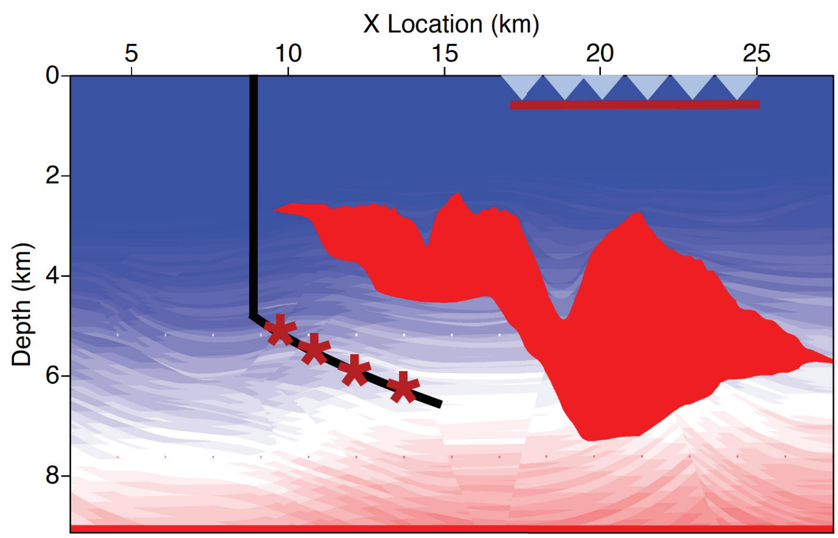


FIG. 9. Seismic-while-drilling acquisition system. (from Kazemi et al., 2018)

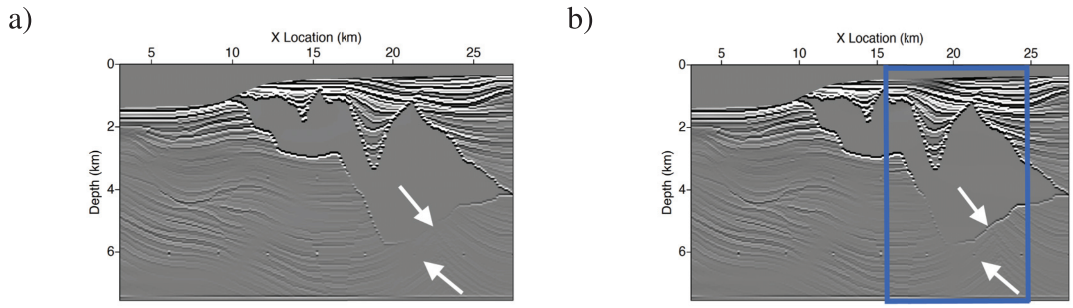


FIG. 10. Prestack RTM imaging result of the Sigbee2a model. (from Kazemi et al., 2018) a) Surface imaging, b) Merged SWD and surface imaging.

## 4. SWD in Full-Waveform-Inversion

In the real world, Full-Waveform-Inversion struggles to precisely estimate subsurface properties because of the lack of a comprehensive acquisition. A new trend for SWD are aimed at addressing this problem. The drill bit generates elastic energy and can be considered as a source of different ray paths, which is in need by FWI to remedy its shortcoming. Kazemi et al. (Kazemi et al., 2020) developed a successive inversion algorithm based on another estimation of drill bit source signature by combining force measurements, top-drive velocity, and drill-string dynamics modelling with topside and bit-rock boundary conditions (Auriol et al., 2020). Their research has shown the potentiality of combining surface seismic and SWD datasets to avoid the local minima in Full-Waveform-Inversion.

In this research Marmousi2 model is used as synthetic model (Figure 11 a). 66 surface seismic sources are deployed near the top of the model. The receivers are densely deployed near the surface with an interval of 10m. A Ricker wavelet with the dominant frequency of 30Hz is used as the surface source signature, while the deeper source signature is estimated by the method mentioned earlier in this part. The first step is applying constant density acoustic FWI to the initial model (Figure 11 b) for an intermediate velocity (Figure 11 c). Then, use this result as starting model to invert for the final solution (Figure 11 d). From the eventual result, there is an obvious improvement of the velocity structure in the deeper section of the model.

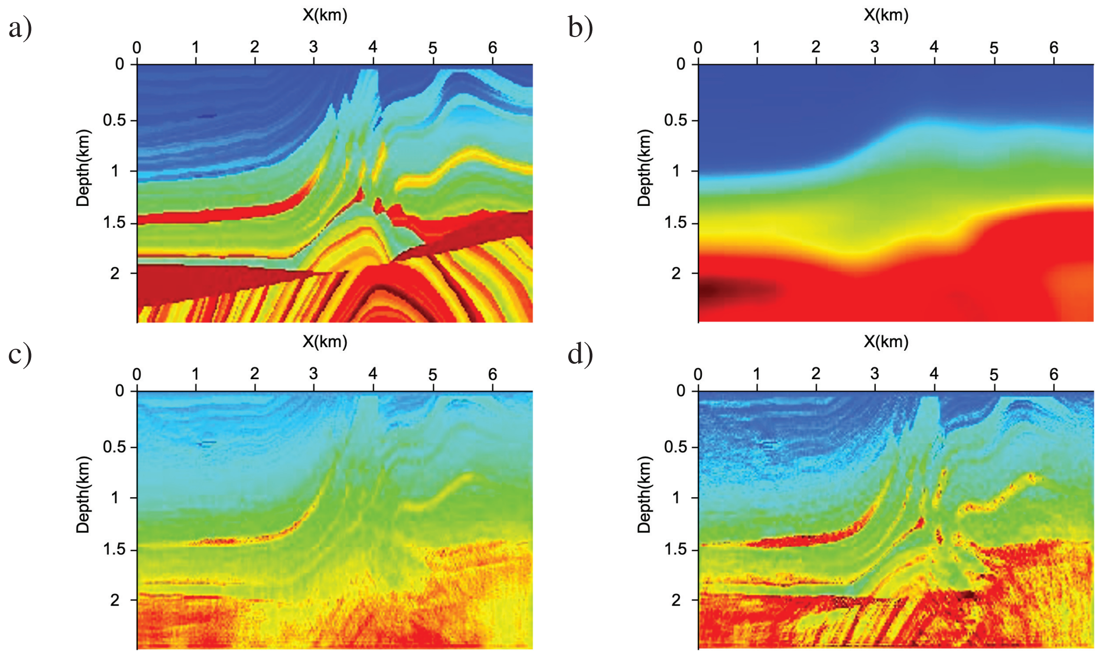


FIG. 11. Surface and SWD FWI algorithm. (modified after Kazemi et al., 2020) a) True model, b) Initial model, c) surface FWI, d) SWD-FWI.

## CONCLUSIONS

This paper reviews the basic principle, the past theories, some lab experiments, field research, and promising applications of a new trend of the seismic-while-drilling method in these recent years (1986-2020). It has been identified that the SWD methods add considerable value either to the drilling operations by providing real-time information or to the surface seismic by generating extra ray paths. The latest feasibility studies reviewed in this paper helps to establish a higher level of confidence in applying SWD to seismic imaging and Full-Waveform-Inversion. One of the challenges in further investigation of this method is better simulating its signals with fewer theoretical assumptions. Thus more physical and numerical experiments should be established.

## ACKNOWLEDGEMENTS

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