Seismic while drilling experiment with diamond drilling at Brukunga, South Australia

Baichun Sun
Curtin University
Baichun.sun@postgrad.curtin.edu.au

Andrej Bona
Curtin University
A.Bona@curtin.edu.au

Binzhong Zhou
CSIRO
Binzhong.Zhou@csiro.au

Andrew King
CSIRO
Andrew.King@csiro.au

Christian Dupuis
Curtin University
C.Dupuis@curtin.edu.au

Roman Pevzner
Curtin University
R.Pevzner@curtin.edu.au

SUMMARY

Seismic-While-Drilling (SWD) utilises drill bit vibrations as a seismic source and receivers at the surface or in a borehole to acquire reverse VSP data. The basic processing technique is based on cross correlation to generate active shot-gather-like profiles. The successful implementation of SWD will yield time-depth information and image around the drill bit, which can aid drilling and geological understanding of the area.

To study the feasibility of using diamond impregnated drill bits for seismic-while-drilling, we conducted a small pseudo 3D SWD experiment at Brukunga, South Australia. It has been used to investigate the signals generated from diamond drilling, and study the potential to use a drill bit as a seismic source.

The drill bit energy for seismic imaging is influenced by the rig power setting, and the state of the drill bit (new or worn bit). The experiment shows that normally the diamond drilling frequency band is wide with strong discrete peaks, however sometimes due to changes in the drilling mode, e.g., increase or decrease the drilling power, the frequency spectrum can be smoothed. The strong peaks in the spectrum mean strong periodicity of the signal and as such, the signals do not lend themselves to standard cross correlation. Thus, we use a generalised cross correlation that produces results similar to an active shot gather-like profile.

Key words: Seismic-While-Drilling (SWD); passive seismic; diamond impregnated drilling

INTRODUCTION

Seismic-While-Drilling (SWD) is a passive seismic technique used in the petroleum industry (Poletto and Mirranda, 2004; Naville et al., 2004; Hardage, 2009). It is based on a principle that utilises the drill bit vibrations as a seismic source, with a receiver array on the ground to produce a reverse Vertical Seismic Profile (VSP) profile. The basic processing technique is based on cross correlation to generate an active shot-gather-like profile. The successful implementation of SWD yields time-depth information and an image around the drill bit. As a result, this enables drillers to "see" around and ahead of the drill bit, and make informed real-time decisions to overcome some drilling related problems. SWD data can also be used to calibrate surface seismic data.

However, using drill bit as a source has some known issues such as a narrow band spectrum and weak energy. The extent of these issues varies with different types of drill bits, drilling power settings and rocks being drilled. The differences in using various types of drill bits are however still unknown. In this paper, to investigate viability of SWD technique using diamond impregnated drill bits in hard rock environments, we analyse the data from a SWD experiment in Brukunga, South Australia.

Brukunga SWD Survey

The Brukunga mine site is located 50 km east of Adelaide, South Australia, in an area of rolling hills of the eastern Mount Lofty Ranges. A main iron-sulphide mineralisation occurs as three steeply easterly dipping conformable lenses separated by waste beds (Taylor, 2003). The experimental drilling program was planned with borehole perpendicular to the dipping mineralisation.

Drilling was completed with Boart Longyear prototype core drilling rig SC9. The drill rig location is shown in Figure 1, where the bore hole is dipping at 60 degrees towards the west, as shown by the arrow. The drilling rotation speed was set between 600 and 800 RPM in this hard rock environment. The drilling was started in September 2011 and completed at a depth of 324m in early April 2012. Because of the slow drilling process, the passive seismic-while-drilling data was acquired in segments over a long time interval, mainly from drill depths between 20m to 50m, and 150m to 190m.

The geophone array layout was limited by the challenging mine topography. Two seismic lines were deployed at the only possible and relatively consolidated flat roads, as seen in Figure 1. The U-shaped Line 1 consists of 84 channels and is located near and around the drill rig. Part of this line are two sets of 28Hz 3-component geophones; one set was located 6m under the drill rig, acting as pilot sensor, the other set was located at the apex of the line 1 U-shape. Line 2 consists of 90 geophones along the access road, as shown in Figure 1. Geophone spacing is 5 m, and 1ms time sampling rate was used.

DIAMOND IMPREGNATED DRILLING

The mechanical method used for the diamond bit is rotary drilling. The rotary drill applies a constant thrust to the bit while a torsional force moves the bit parallel to the rock surface (Maurer, 1967). The normal force and torsional force interacting with the rock produce required elastic waves for the seismic study. Extensive study by Sun (1996) has shown that significant differences in acoustic properties can be found among different drilling situations, such as new bit, worn bit, etc. The study also shows that acoustic signals from worn bits were higher and rougher compared with signals from new bits; the rougher the signal from the drill bit, the better the energy for seismic use. Hence, although the driller will try to keep drilling as smooth as possible, the energy from the bit-rock

interaction could be very variable, giving us an opportunity to use the drill bit as an effective seismic source.

Ideally, we would record the pilot signal at the drill bit to reconstruct the reverse VSP profile. However, we cannot easily attach a sensor next to a real working drill bit. Consequently, we do not have an exact vibration signature or so-called pilot signal of the drill bit. At this stage, most seismic-while-drilling experiments place a pilot sensor on the drill rig to get a close (and delayed) replica of the drill bit signal. However, in our experiment, due to engineering difficulties, the pilot sensors were only buried under the drill rig.

SIGNAL ANALYSIS

In this experiment, the buried pilot sensors recorded the vibration signatures from the drill rig & the drill bit, as well as noises from the nearby drill yard. The recorded drill bit signal at the pilot sensor is filtered by the formation transfer function, so the true drill bit signature (the pilot signal) is expected to be relatively low in amplitude compared with the drill rig vibrations and other environmental noises.

It is shown that the rig power setting, the state of the drill bit and its interaction with the rock determine the seismic energy. The power variation can be easily tracked, however the other two factors are nor easily monitored in real time. Figure 2 shows 2 seconds of the pilot signal during drilling. The three panels in the figure correspond to different drilling depths. The drilling amplitude spectra are wide, ranging from 20 to 450Hz. The spectra are generally correlated, but there are some variations. High frequencies above 300 Hz are more obvious in (b) and (c) than in (a). The peak frequency is changing with depth as well. One possible explanation of these differences is that to overcome more friction from bore hole when drilling deeper, the rig power setting might need to increase. Therefore, we expect power spectra to be slightly different on drilling from shallow to deep. However, (b) and (c) spectra plots are from 07 March and 08 March, during which time the bit depth change is small, so their spectral differences are possibly due to the bit rock interaction.

In Figure 2, we also observe that the spectra of diamond-impregnated drilling signals are wide, but contain some strong peaks, which is more obvious in Figure 3. The strong periodicity of the signal (strong peaks in the spectra) make construction of the reverse VSP seismograms by cross correlation difficult.

Figure 3 shows a continuous pilot record of drilling from no-drilling to drilling. When drilling is not engaged, the spectrum shows very strong spiky noises, which were caused by drill yard generators, mud circulation motor…, etc., these noises are also observable during drilling, and other weak background noises are uniformly distributed. When drilling is started there is a clear power increase and decrease around 590s, the variation possibly represents the drilling engagement. The corresponding spectrum shows drilling energy increases significantly: its spectrum is wider and smoother when drilling power variation occurs.

To better present the spectrum variation with time, we plot the time frequency analysis of the same pilot signal from Figure 3; Figure 4 shows the time frequency analysis computed on a 0.5s running window with 50% overlap. The x-axis is time and the y-axis is frequency. It clearly shows a wider spectrum around 590s. So the drilling variation creates a wider usable energy band for seismic imaging.

So far we have only shown the pilot signal at near rig offset channels, where we have observed strong fundamental frequencies components and their harmonic overtones. However, at far offsets, the spectrum variations with different channels become more obvious. This is because the direct arrivals from drilling are attenuated, and become less dominant, but the random noises, surface waves and other waves, such as refraction, are more prominent.

CROSS CORRELATION

The vertical component pilot sensors below the rig are used for cross correlation with the surface receiver array. We used the Roth correlation (Roth, 1971) in order to suppress the strong periodicity in the signals. Generalised cross correlation can be expressed as

$$R_{pg}(\tau) = F^{-1}(\Psi(\omega)P(\omega)G^*(\omega)), \quad (1)$$

where $\psi(\omega)$ is a weighting function. $\psi=1$ corresponds to the standard cross correlation. $P(\omega)$ and $G(\omega)$ are the Fourier transforms of the pilot and geophone recordings, the asterisk represents complex conjugation. In the Roth correlation, the weighting function $\psi(\omega)$ can be chosen as the spectrum of the pilot signal, as shown below, where $w(\omega)$ is a smoothing window function.

$$\Psi_{Roth}(\omega) = w(\omega)\frac{1}{P(\omega)P^*(\omega)} \quad (2)$$

We tested the cross correlation at different times of the drilling process. Figure 5 shows the comparison results of the Roth cross correlation, normal correlation and their average spectra,**:** (a) corresponds to normal cross correlation (1000s time length) and its spectrum; (b) corresponds to 200s (550s-750s) Roth's correlation result, (c) corresponds to 200s (750s-950s) Roth's correlation, (d) corresponds to 1000s (0-1000s) Roth's correlation result.

In this figure, subfigure (a) shows that the normal cross correlation does not work well. After correlation, the signals are low pass filtered. Subfigures (b) and (c) show two consecutive 200s correlation results: correlation in (b) is derived from the time when there is a strong amplitude increase during the drilling, correlation in (c) is from 200s long relatively smooth drilling period. As discussed above, (b) should have a more suitable spectrum for the cross correlation than (c), and thus its direct arrivals are easier to identify. The average spectrum in (c) is similar to the spectrum in (d), although correlation in (d) uses 5 times as long a trace. This might be understood from the fact that the drilling is generally smooth, and an increase in the number of samples will not change the fluctuation of spectrum, but just increases the resolution of the spectrum (Claerbout, 2004).

Figure 6Error! Reference source not found. is a weight drop shot gather at the drill rig. The result is comparable with the cross-correlation seismogram, however, as shown in pilot channel spectrum, its peak energy is above 100 Hz, so SWD cross correlation seismogram frequencies are higher than active seismic, as known that the useful spectrum in active seismic is usually below 100 Hz.

The cross correlation in Figure 5 shows good direct arrival from the drill rig, but the drill bit signal is not easily recognised in the figure. In order to identify the drill bit signal, we look at cross correlated data corresponding to different depths. This will allow us to try to detect changes in the data due to the changed position of the drill bit, while the signal corresponding to the drill rig stays stationary. For comparison

we also made a 2D elastic finite difference model, which is made of isotropic medium, velocity is 5000m/s and density is 2.8g/cc. We model two sources: source one is at surface with an input Ricker wavelet, and source two is located underground with varying depth. The starting location of the second source is changing from depth of 150 m along an incline of 60 degrees with spacing of 2m. We consider 20 source positions. **Error! Reference source not found.**Figure 7 (a) shows channel 30 synthetic data cross correlation receiver gather. Figure 7 (b) shows Brukunga SWD channel 1 (100m from drill rig next to the quarry) cross correlated with the pilot data, the bit depths are from 150m to 190m (75m to 95m horizontal distance to the rig). As the drill rig signal is stationary, the high amplitude constant arrival corresponds to drill rig signal in both the synthetic and real data. The drill bit arrival is shown on synthetic data by an arrow. For real data, the drill bit move out is not as clear as for the synthetic data, however, both data sets indicate a similar character above the drill rig arrival.

DISCUSSION

We have presented the analysis results of our seismic-while-drilling experiment at Brukunga, South Australia. For the surface receivers, the strongest energy received is from the drill rig, and the observed drilling signal spectrum is wide, with strong discrete peaks.

The experiment results show that by simply changing the drilling mode it is possible to improve the cross correlation. We also observed that the seismic energy varies with drilling depth. As the driller tries to maintain the same weight-on-bit, we observe the peak energy and bandwidth change within only two days of recorded data, which is possibly due to changing bit-rock interaction.

For the Brukunga SWD experiment, we were able to initially characterise the diamond drilling signal in hard rock environment. While it is challenging to identify the diamond drill bit signal in the real data, the synthetic studies indicate that trying to identify the drill bit signal through the changes in the data due to the changing depth might be possible. Hence, to better understand the diamond drill bit signal, more experiments are required. In addition, a better imaging algorithm needs to be developed for the case where the pilot signal is unavailable.

Figure 1 Seismic-while–drilling receiver line geometry at Brukunga, South Australia. Drill rig is located at the centre of U-shaped line 1, the arrow indicates the drilling direction.

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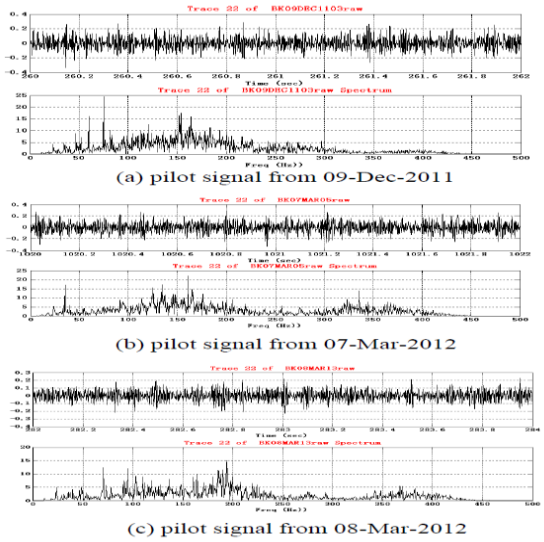


Figure 2 Seismic pilot traces and their amplitude spectra: Panel (a) is from early drilling at shallower depth (~50m), (b) and (c) are from deeper drilling in 145m and 160m, respectively. Almost all of the energy is concentrated between 20-450 Hz, but with strong discrete peaks. The

differences in the spectra include more high frequencies in (b) and (c), and shifted peaks.

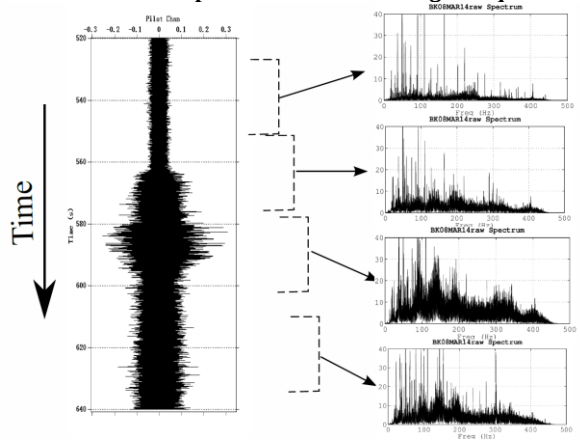


Figure 3 Spectra of Brukunga pilot signal during different drilling modes. The strong discrete peaks are observed in all the three amplitude spectra.

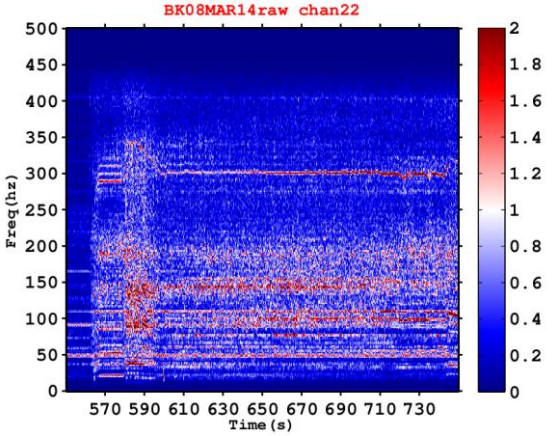
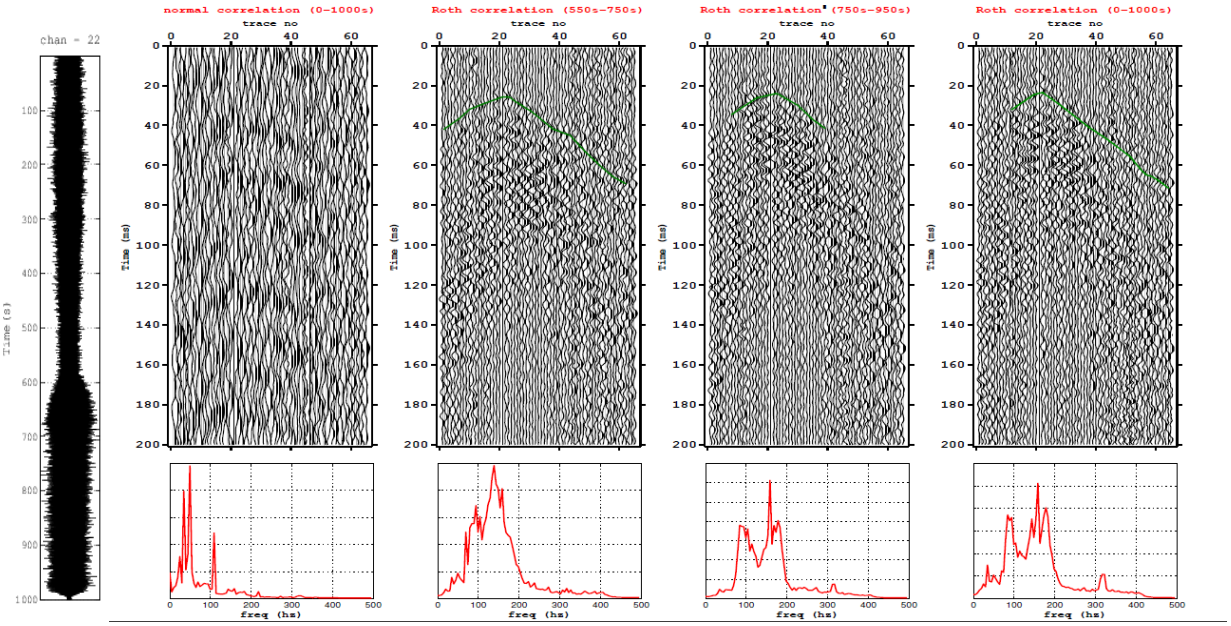


Figure 4 Time frequency analysis of data shown in Figure 3. The spectrum widens around time of 590s, when drilling power variation occurs – it possibly corresponds to drilling engagement.



(a) (b) (c) (d)

Figure 5 Roth cross correlation with different time length signals and their average spectra. Left panel shows 1000s drilling pilot signal, (a) is normal cross correlation, which is very periodic, (b) and (c) are formed by Roth correlation of 200s long traces, (b) is correlation during amplitude variation (550s-750s, changing power); the peak frequency is smoother in contrast to (c) (750s-950s, smooth drilling), (d) is from Roth correlation of 1000s long traces, which is quite similar to (c).

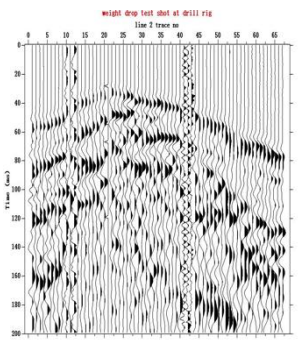
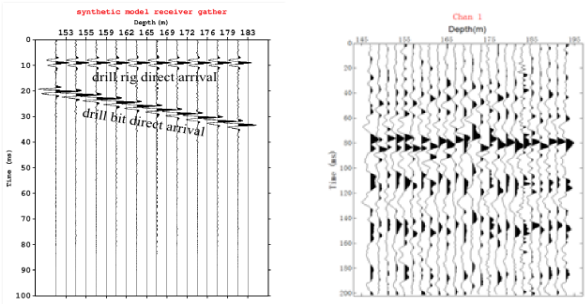


Figure 6 Weight drop active test seismogram, shot is located at the drill rig position.



(a) (b)

Figure 7 Cross correlated traces corresponding to varying depth of the drill source: the x-axis is distance, and the y-axis is time. Panel (a) shows synthetic receiver gather, where the rig and bit signals are separated, panel (b) shows Brukunga SWD Chan 1 receiver gather.