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Evaluation of the forward-looking capability of conventional borehole radar

Binzhong Zhou
CSIRO Energy Flagship
PO Box 883, Kenmore, QLD 4069
Binzhong.Zhou@csiro.au

Matthew van de Werken
CSIRO Energy Flagship
PO Box 883, Kenmore, QLD 4069
Matt.Vandewerken@csiro.au

SUMMARY

There is a strong need to develop real-time imaging technologies to enable the driller to 'see' the subsurface structures ahead of the drill-bit and around the borehole during borehole drilling. One of the ways to realise such imaging while drilling is to use borehole radar (BHR) techniques. In this paper, a conventional non-directional mono-static BHR will be evaluated for its forward-looking capability by using the data collected at an abandoned mine site at Brukunga, South Australia. Here we demonstrate that the conventional BHR can be electrically coupled on to a conductive wire or drill-rod whilst a guided wave is induced along the axial wire or drill string making it possible for imaging ahead of the drill-bit by integrating the BHR with the steel drill string. The drill-rod ahead of the BHR acts as a forward-looking antenna. When the guided wave travels to the end of the drill-bit, part of the energy is reflected by the drill-bit and the remaining energy radiates in front of the drill-bit, and is reflected by the geological/electrical discontinuities, recorded by the BHR. The forward-looking capability of the BHR is about 2-6m in the tested borehole section.

Key words: Borehole radar, guided EM wave, forward-looking antenna.

INTRODUCTION

A key research driver and challenge in the mining industry is to discover and develop new resources cost-effectively, productively, and safely. Drilling plays a key role in collecting exploration information. However, drilling in hard rock today is largely blind. In the words of a Chevron engineer "right now it's like we're driving with the headlights turned off at night. The only thing we can do is stop the car after we've hit something" (Ahmed, 2000; Drilling Contractor, 2008). Such an approach makes drilling less cost effective than it can be, and contributes to many exploration mistakes; it often results in holes that fall short of their desired target, over-drilling of barren formations, or simply missing the targets. Other common problems with the blind drilling of deep drill holes are losses of drilling equipment and lost time and cost associated with stuck bit problems. Like most hazards, the risk can be circumvented or mitigated with prior knowledge and planning. For example, a change of bit, drilling mud, or the drilling forces or drilling direction can significantly improve the drilling efficiency and reduce risks if what lies ahead is known and where the target is located.

One way to turn on the 'drilling headlights' is through imaging-while-drilling (IWD) using techniques such as seismic-while-drilling (SWD) used in the petroleum industry (Rector and Marion, 1991; Poletto and Miranda, 2004; Naville et al., 2004; Anchliya, 2006) and engineering (Soma et al., 2004; Reppert, 2013, Zhou et al, 2014). However, realization of SWD is becoming more challenging due to that the rotary-cone (RC) drill bit has been replaced by the Polycrystalline Diamond Compact (PDC) bit, which has been identified as a less effective seismic source (Anchliya 2006). An alternative way for IWD is to use borehole radar (Stolarezyk and Stolarezyk, 2004; Mancorda et al, 2009).

Borehole radar (BHR) is a variation of surface ground penetrating radar (GPR), specifically designed for subsurface imaging in boreholes (Ebihara et al, 1998; Slob et al, 2010). It can be operated in either single hole reflection or cross-hole transmission (Zhou and Fullagar, 2001; Slob et al, 2010). BHR has many applications, including cavity detection, fracture mapping, coal mining, hydrological investigations, stratigraphic mapping, geotechnical evaluation, and orebody delineation.

There are few BHRs designed for forward-looking along the borehole axis (Miwa et al, 1999; Murray et al, 2000; Mancorda et al, 2009; Mason 2010) due to limitations of possible borehole antennae geometry imposed by the borehole dimension. The majority of current BHRs are designed for side-looking along the borehole radial with a dipole antenna (Lytle and Laine, 1978; Sato and Thierbach, 1991; Ellefsen and Wright, 2005).

The dipole antenna of a conventional BHR generates optimum EM waves in the radial direction of the antenna but with an axial null EM wave radiation. However, such radiation pattern can be changed if the BHR is attached to a conductive wire or is used in a conductive saline-water-filled borehole; guided BHR EM wave propagation can be observed along the wire (Wright et al., 1984; Sato and Thierbach, 1991; Ebihara et al., 1998; Guy and Radzevicius, 2001; Mason et al., 2008) and the conductive water column (Dubois, 1995; Vogt, 2004; Mason et al., 2008). This guided BHR EM wave can potentially be used for forward-looking. In this paper, as part of our effort to seek and develop looking ahead BHRs for IWD, we use specially designed BHR experiments to evaluate whether a conventional BHR, like the mono-static version from

Geomole Pty Ltd, can be configured to act as a forward-looking antenna.

THE BOREHOLE RADAR SURVEY

The BHR experiments were conducted at the abandoned Nairne Pyrite Mine, at Brukunga, South Australia. The mine site is located in the Southern Mount Loft Ranges, known locally as the Adelaide Hills, about 40km east of Adelaide. A main iron-sulphide mineralisation occurs as three steeply, easterly-dipping, conformable lenses separated by waste beds (Taylor and Cox, 2003).

A mono-static slimline 10-125 MHz pulsed BHR from Geomole as described by Mason et al (2008) was used for the experiments. The BHR was deployed by directly attaching the BHR to a winch like a conventional BHR survey or in geophysical logging. The BHR was turned on and it started to record continuously before it was attached to the winch cable. Figure 1 shows photos of the preparation for the survey and the attached BHR loaded into the borehole at the borehole collar (see Figure 1 photo (f)). This test was performed for a simulated drilling operation with a pre-drilled borehole, in which the BHR was attached to a steel winch cable with different configurations. The winch cable simulates a normal drill string in a normal drilling operation. The winch was used to facilitate the BHR survey similar to a normal geophysical borehole logging. The maximum depth of the survey was about 260m.

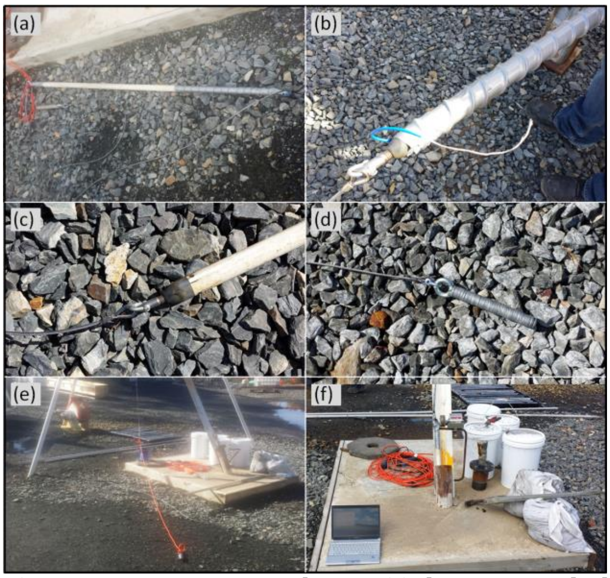

Figure 1 BHR survey at Brukunga: (a) the BHR attached with a conductive steel cable; (b) a conductive wire wrapping around the BHR antenna for coupling with the attached conductive steel cable; (c) The connection of the conductive steel cable with the BHR; (d) the weight attached to the end of the steel cable; (e) a non-conductive nylon rope for separating the conductive winch steel cable from the BHR; (f) the BHR, attached to the winch steel cable, ready for logging the borehole.

Five types of BHR configurations were used for this survey:

1) Configuration 1: This configuration simulates a conventional BHR survey in which a bare BHR was attached to the conductive winch steel cable with a 3m long non-conductive nylon rope for decoupling the BHR with the winch cable.
2) Configuration 2: The BHR was directly attached to the winch's steel cable. The winch cable acts like the steel drilling string. Therefore, this configuration simulates the fibreglass-drill-rod-integrated BHR directly attached to the top drill string. The EM waves that radiated from the BHR coupled with the winch cable and the cable acts as a waveguide and becomes a back-looking antenna.
3) Configuration 3: This configuration was the same as Configuration 2 but with a 1.5m steel cable plus a 0.3m weight (1.05kgs) for straightening the cable (see Figure 1 (a) – (d)). The weighted cable was attached to the bottom of the BHR (antenna side). The 1.8m weighted cable simulates the drill-rod (with the drill-bit) attached at the front of the fibreglass-integrated BHR.
4) Configuration 4: This configuration was the same as Configuration 3 but with a 3m non-conductive nylon rope added between the BHR and the steel winch cable for decoupling the BHR with the winch cable.
5) Configuration 5: This configuration was the same as Configuration 4 but with a 3.3m weighted steel cable at the front of the BHR instead of a 1.8m long cable.

THE RESULTS

Raw BHR data

Figure 2 shows an example of collected raw data for Configuration 1. For this configuration, the BHR acts like a conventional side-looking BHR. Side reflections from the borehole surrounding are clearly observed, indicated by the portion of the red horizontal line where the rock is relatively resistive.

Note that each BHR survey logged the borehole twice: once whilst descending and the other whilst ascending the borehole. The data analysis will focus on one of the two data segments (descending or retrieving). It is important to also note that the BHR data in the conductive part of the borehole below a depth of 134m (at trace ~540) vary little between each of the configurations. This effect is caused by the waveguide behavior of the conductive borehole and will not be discussed further in this paper.

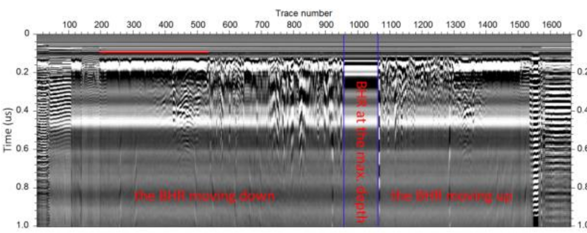

Figure 2 Conventional BHR survey with the bare BHR attached to the winch steel cable with a 3m long non-conductive nylon rope.

Data analysis

The goal of the BHR survey was to evaluate the forward-looking capability of a conventional Geomole BHR. This can be only assessed in the resistive part of the borehole where the side-reflections and the steel-cable guided waves can be observed for different configurations. The borehole radar data from the resistive part of the borehole are marked by the horizontal red line in Figure 2.

Figure 3 shows the segment of the BHR data (Figure 2) from the resistive section of the borehole for Configuration 1 in which the BHR was separated from the winch's steel cable by a 3m non-conductive nylon rope. This test simulates a conventional BHR survey. From the raw data shown in Figure 3(a), it is clear that there are many side/radial reflections from surrounding rocks of the borehole. The observation of side reflections is due to the fact that the BHR has a dipole transceiver antenna that generates optimum EM waves in the radial direction of the antenna but with an axial null EM wave radiation. To enhance the reflections, a 61-traces-moving average filter is applied to the raw data and the average-filtered result is subtracted from the original data to suppress the vertical stripes, which possibly relate to the antenna reverberations and the result is presented in Figure 3(b). A 0.1µs automatic gain control (AGC) was applied to Figure 3(b) to balance the reflection amplitudes as shown in Figure 3(c). Based on Figure 3(c), it is not difficult to see that the BHR can see further (more reflections in late time) in the deeper part of the section than in the shallower part of the borehole. This observation is consistent with resistivity log in Figure 4 – the resistivity increases with the depth in this part of the borehole. In general, such BHR does not have any forward-looking capability. However, if there is an inclined structure intersecting the borehole, the conventional BHR can be used as a forward-looking tool as shown by the red line reflection in Figure 3(c).

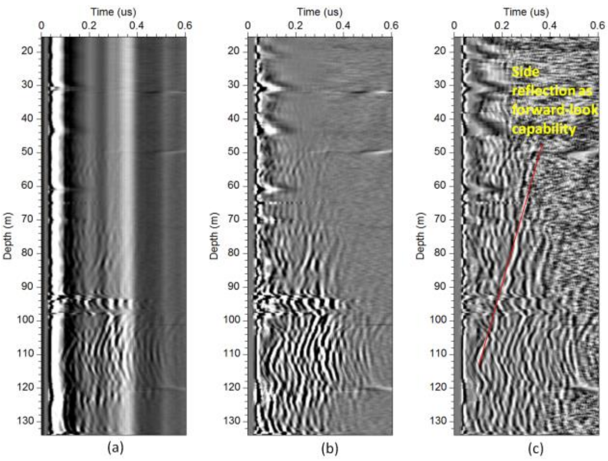

Figure 3 The BHR data cutting out from the resistive part of the borehole (marked by the horizontal red line) in Figure 2 for Configuration 1: (a) The raw data; (b) the same as (a) after suppressing the direct arrivals; (c) AGC applied to (b).

Figure 4(c) shows the segment of the BHR data from the resistive part of the borehole using this configuration, after filtering and AGC were applied. In addition to the side reflections observed in the test of Configuration 1, there are many strong, near parallel, diagonal reflection events dominating the time section. These diagonal events are caused by the axially guided EM waves travelling up the wire, reflecting at lithological discontinuities, and then travelling downward to the BHR, and recorded by the BHR (Mason et al., 2008). These events are marked by the solid red lines as back-looking events. The reflected guided waves can be observed from the discontinuities up to 24m away with an estimated velocity of ~100m/µs. The bedding planes along the borehole can be pinpointed by these reflected guided-wave events, which can be traced back to the main resistivity boundaries of the resistivity log as marked by the horizontal magenta lines. In addition to the guided reflections, there are also multiples of guided waves marked by the red dashed line. The multiples are caused by the reflected guided waves reflecting upward by the BHR along the wire and enduring the same travel path as the primary guided wave.

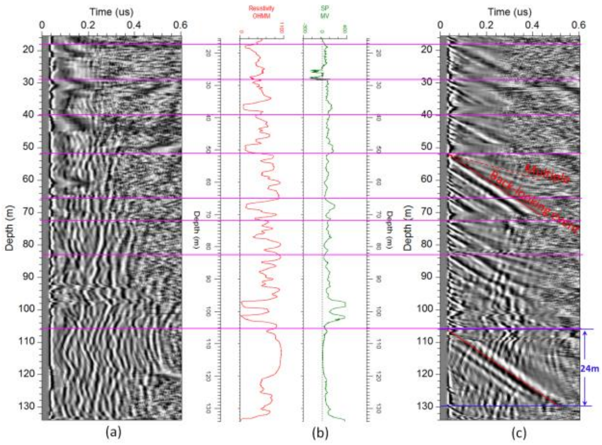

Figure 4 Comparison of borehole radargrams with borehole logs: (a) The same BHR data with AGC in Figure 3(c) ; (b) The resistivity and SP logs; (c) The BHR data with AGC for Configuration 2.

Figure 5 presents the BHR data for Configurations 3, 4, and 5. Except for the axial-backward- and radial-side-looking reflection events, Figure 5(a) also has extra events: the axial-forward-looking reflection events as marked by the magenta lines. Based on our estimation, the forward-looking events have a reflection range of 4 – 8m. The front steel cable is only 1.8m. The forward-looking events can also be observed from the data for Configuration 4 and 5 in Figure 5(b) and (c). This observation suggests that the front steel cable (or the drill-rod) can act as an EM wave antenna radiating EM waves beyond the steel cable /drill-bit by 2 – 6m and reflecting back. That is, if the BHR is configured in such a way, it will have a 2-6m forward-looking capability.. Such configuration makes it plausible to use a conventional BHR for real-time imaging ahead of drill-bit.

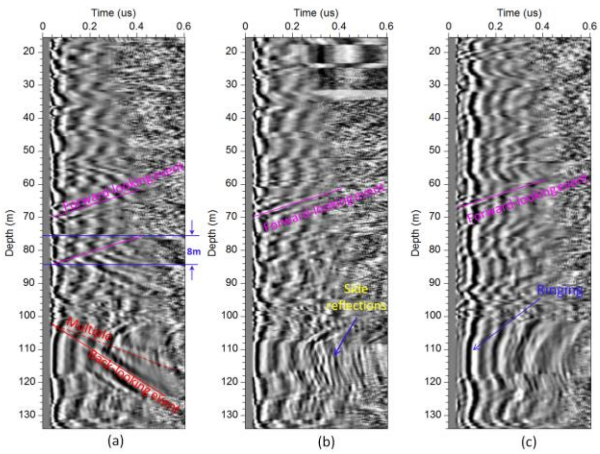

Figure 5 BHR sections with forward-looking events: (a) Configuration 3; (b) Configuration 4; (c) Configuration 5.

CONCLUSIONS

Based on this analysis of the BHR data collected at Brukunga, the following conclusions are made:

- The dipole antenna of a conventional BHR in a wire-free borehole has an axial null and can only look sideways around the borehole;
- conventional BHR can be electrically coupled to a conductive wire or drill-rod to induce a guided wave along the axial wire. This property provides some potential for the conventional BHR to image ahead of the drill-bit by integrating the BHR with the steel drill string. The drill-rod ahead of the BHR in some respect becomes part of the radiating antenna. When the guided wave travels to the end of the drill-bit, part of the energy is reflected back by the drill-bit and the rest of the energy radiates from the drill-bit. This provides potential for energy to be reflected by the geological/electrical discontinuities, and recorded by the BHR;
- The forward-looking capability of the BHR was found to extend about 2-6m in the tested borehole section.

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