



Seismic while diamond drilling

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SUMMARY

We have performed tests at the Boart Longyear drilling test site at Brukunga, South Australia, with grouted geophone sensor strings in nearby drillholes that demonstrate the feasibility of using diamond drilling process as a source to gather high quality seismic velocity data in the earth. These geophone sensor strings and the seismic while drilling methodology develop dare envisaged for “life of mine” sensing and geological characterisation. Thus, various tests have been performed to evaluate whether the gathered data might be useful for various future applications from advanced exploration and geological characterisation through to mining and extraction. Various modifications of the seismic string installation with respect to 1-C and 3-C sensor pods and grouting method were trialled and all configurations were generally found useful. However, some configurations are better suited for tomography and others better for later micro-seismic analysis.

The drill as a seismic source was found to be rich in both P and S wave modes with reasonable energy from 10 Hz to over 500 Hz, at distances of up to 200m from the diamond drill bit. Small modifications to the drilling procedure allowed us to perform checks on the data quality and acquisition system. The lack of a measured “zero-time” or measured source signature with the SWD creates serious challenges for implementing conventional cross-well tomography algorithms with the drill-cutting as a seismic source in one hole and the geophone string in another. Thus, the tomography inversion algorithms must be changed, and a good reference velocity model used as a starting seed for inversion. This is where the slight modifications to drilling procedure may provide extra data. A configuration of two boreholes with permanent sensors and the drilling of another hole in line with the first two allows cross-correlation methods to reasonably extract travel times. However, the repeating pattern of energy generated by the seismic source due to drill rotation at 10-40 Hz presents challenges to this approach too, which we partially overcome with use of time-gating via a reference velocity model collected via straightforward Zero Offset vertical seismic profiles. Despite challenges, seismic while drilling with diamond drill rigs in conjunction with geophone sensor arrays is feasible and should provide every useful life-of-mine data.

Key words: Tomography, borehole, seismic, ZVSP

INTRODUCTION

The cross-hole tomography project is a R&D partnership with Boart Longyear and RoqSense Pty Ltd to create a driller installable, permanent, cross-borehole tomography sensor strings in drilled boreholes. As exploration and development drill-holes must be sealed before abandonment, usually with grout, by regulation nowadays it seems an opportunity to emplace sensors in the hole while grouting could make significant differences the ability to further discover and define mineral resources. Tomography was chosen because it provides what we believe is critical information between drill-holes and away from drillholes to allow better decision making in the placement of further drilling and to more robustly interpolate measurements on core away from the borehole. The project envisioned testing the ability to perform both active and passive imaging. Active imaging will use the drill rig to make a “signal” for the sensor strings (the drilling process of cutting the rock or dropping drill rods to make a hammer signal). Active imaging envisions the use the drill-rig (position) to perform cross-well tomography from bit to an instrumented hole, or be in line-with two other boreholes to perform interferometric imaging with a known source location. The latte is a form of passive imaging with known source properties. Lastly, the ability to use nearby seismic noise sources to create data is also to be evaluated. In this paper we look at out first analysis of using tw instrumented holes with the drig rig supplying the seismic energy.

DESIGN AND INSTALLATION

The scarcity of electronic components in 2022 meant that the ADI sensor strings were analog, omni-directional, geophone sensors with digital data conversion performed by commercially available seismographs on the surface. Such an approach allowed the strings to be manufactured overseas with reasonably high integrity with respect to sealing and pull strength-resistance with respect to damage.



Figure 1. Site Layout at Brukunga-Pyrite Rd, Adelaide Hill (SA). Seismic sensor string were deployed in Holes CBHT06-08 50m and CBHT09-10 (200m).



Figure 2. The 200m seismic string is pictured in the left panel and the (1-C and 3-C) sensor pods are 38mm diameter at 10m spacing. The strings are mounted on a tremie pipe and concrete-grout is pumped into the pipe until it flows out of the annulus of the hole at surface. This procedure is carried by the drilling crew in right panel and is compatible with current practice of sealing and completing holes in exploration.

The flexibility of using surface seismographs was needed for the first set of experiments where we were looking to understand better the seismic energy from diamond drilling and possible sensors spacing and 1-C versus 3-C configurations. The first three holes (CBHT06-CBHT08) were only 50m depth and both standard concrete grout and a viscous bentonite mud were trialled to seal the borehole and couple the sensors to the rock formation. Both types of sealant-fill coupling worked well. The sensor string was taped to a plastic tremie pipe and fed into the open hole. The grout-mud was pumped down the tremie pipe until reaching the surface again via the outer annulus between pipe and borehole wall. Horizontal components were introduced in all sensor strings and used smaller geophone elements to allow the sensor pods to be 38mm in diameter. Vertical orientation (along the cable direction) geophones proved easiest to analyse later and provide the narrowest diameter sensing, allowing sensor pods less than 38mm, which

makes for a installable sensor string in HQ and Nq diameter holes. A configuration of 10m sensor pod spacing configured as 5 vertical sensors pods and then a three-component sensor pod allowed the sensor string to theoretically be installed in NQ dia hole without becoming prohibitively expensive and sample the wavefield with fairly high spatial resolution. Cross-directional or Horizontal geophone are desired by the mining industry for seismic hazard monitoring and life-of-mine analysis so these were included in second generation, and also to help further understand the wavefield in later analysis.

All of our test holes (Map of hole locations at the Brukunga test area in Figure 1) were HQ because these were the rods and drill-set up on site. Our learnings, tooling and method are applicable to NQ diameter generally used in exploration. The installation process was done entirely by the drilling crew run by Ben Crettenden, with not a geophysicist in sight. A significant aspect of the tomography experiment design was to devise a system that could be installed and operated without “experts” performing the work rather than to purely make new technical achievements.

EXPERIMENTS AND RESULTS

The lack of a measured “zero-time” or measured source signature with the SWD creates serious challenges for implementing conventional cross-well tomography algorithms with the drill-cutting as a seismic source in one hole and the geophone string in another. Thus, the tomography inversion algorithms must be changed, and a good reference velocity model used as a starting seed for inversion. This is where the slight modifications to drilling procedure may provide extra data..

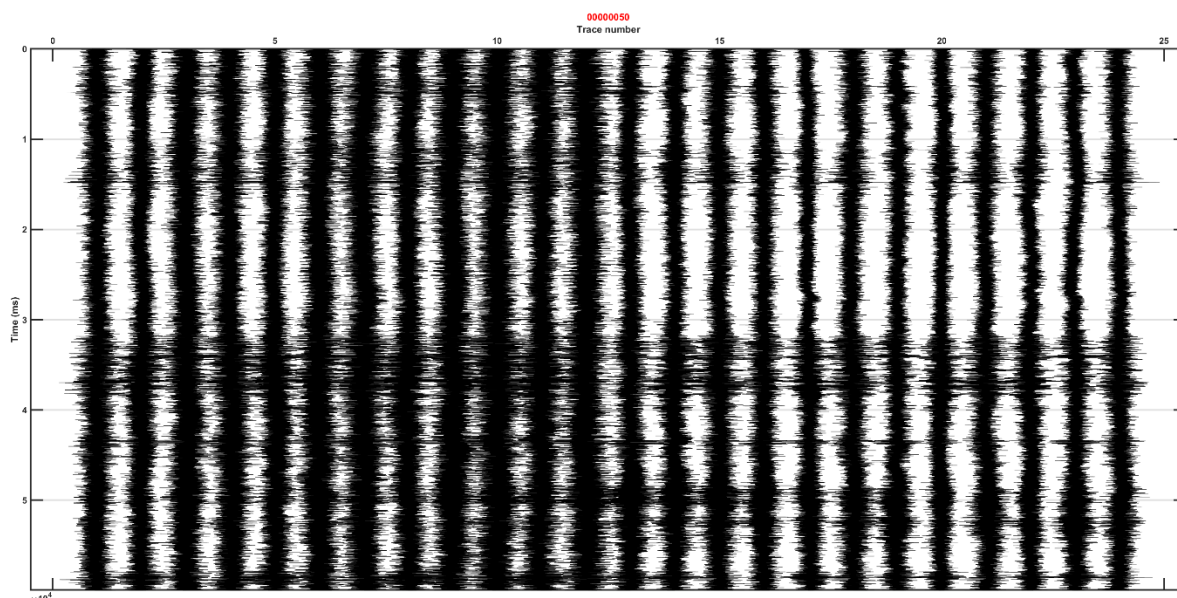


Figure 3. An example of seismic while drilling showing a 30 second time series data from alternating 1-C and 3-C geophone pods spaced 5 m apart into two separate boreholes. Traces 1-12 are 100 m away and traces 13-24 from sensors 50m away from the drill rig. In this example there is some variation in the rotation and downward force upon the drill bit.

The most useful data sets collected so far is a configuration of two boreholes with permanent sensors and the drilling of another hole in line with the first two allows cross-correlation methods to reasonably extract travel times. However, the repeating pattern of energy generated by the seismic source due to drill rotation at 10-40 Hz presents challenges to this approach too, which we partially overcome with use of time-gating via a reference velocity model collected via straightforward Zero Offset vertical seismic profiles. It should be noted that the drilling crew not only operated the drill rig but also collected the seismic data during drilling as we largely automated the collection process.

The seismic energy from diamond drilling was found to be reasonably energetic and broadband (Figure 3 and 4) with the acoustic energy spread between 10Hz and 1000 Hz. Most of the energy was found to be between 20Hz and 600Hz in examining data from the 50m 3-C geophones. This seismic while drilling energy bandwidth equates to a (theoretical) spatial resolving power of approximately 3m, which is far better than surface seismic surveys can achieve (10-25m). It was decided to collect data at 1 ms sample rate, which proved able to capture the most useful range of frequencies (10-450Hz).

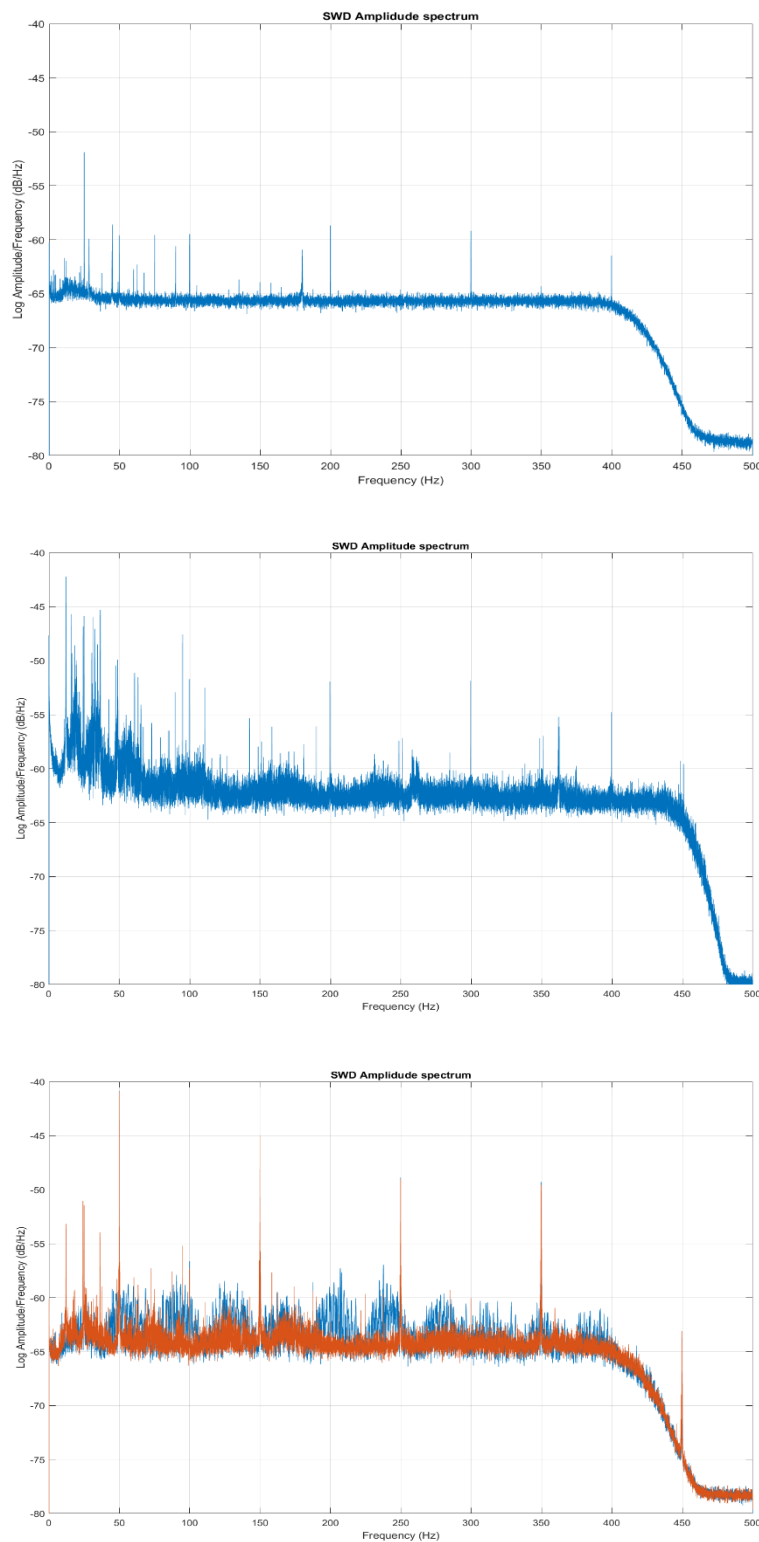


Figure 4. Amplitude spectra of background-system noise (upper panel), diamond drilling (middle panel), and a comparison of a rod-drop (blue) versus diamond drilling (orange). Power-grid related noise is evident in narrow spectral lines at 50 Hz and harmonics. The seismic energy from the diamond bit and rod drop impact are broadband with over 500 Hz available (tested with 0,5ms sample rate). Most data were collected with 1ms sample rate, achieving more than 400 Hz of usable frequency content.

To gather data a few methodologies were developed:

- Hammer blows near the hole collar were used to develop reference velocity with depth at each borehole installation (ZVSP).
- Core-break moment captured by drilling crew as a “seismic tensile impact” source.
- Rod-drop, where the drill string is lifted by 10 to 30 cm and then “let go” to produce a hammer blow at the bottom of the drill-hole.
- Measurement while diamond drilling collecting 30 second records every metre.

Rod-drop impacts proved to be a reliable means to generate “check” data and independent travel-time data for cross-borehole tomography. The cross-check data with core-breaks, rod-drops and hammer on surface were critical in understanding the data. These would be not normally be done in practice; however, these data sets aided understand critically the rod drop or equivalent with a decent zero time would make for robust data by itself.

Diamond drilling appears to produce predominantly s-wave energy. Analysis of data from all geophone orientations and arrival times of the main energy (via correlation methods) points to S-waves being predominate. Data from the 200m CBHT experiments indicate that water pumps, to reduce acid mine drainage in the area, are the predominate seismic energy source, and these produce P-waves mostly and are helpfully located in assisting in analysis it appears, but this analysis is not reported here..Spectral analysis of the 50m data does not indicate the same level of pump seismic noise. Perhaps indicating that the pumps were turned on between collecting the 50m data (early winter) and the 200m data (spring).

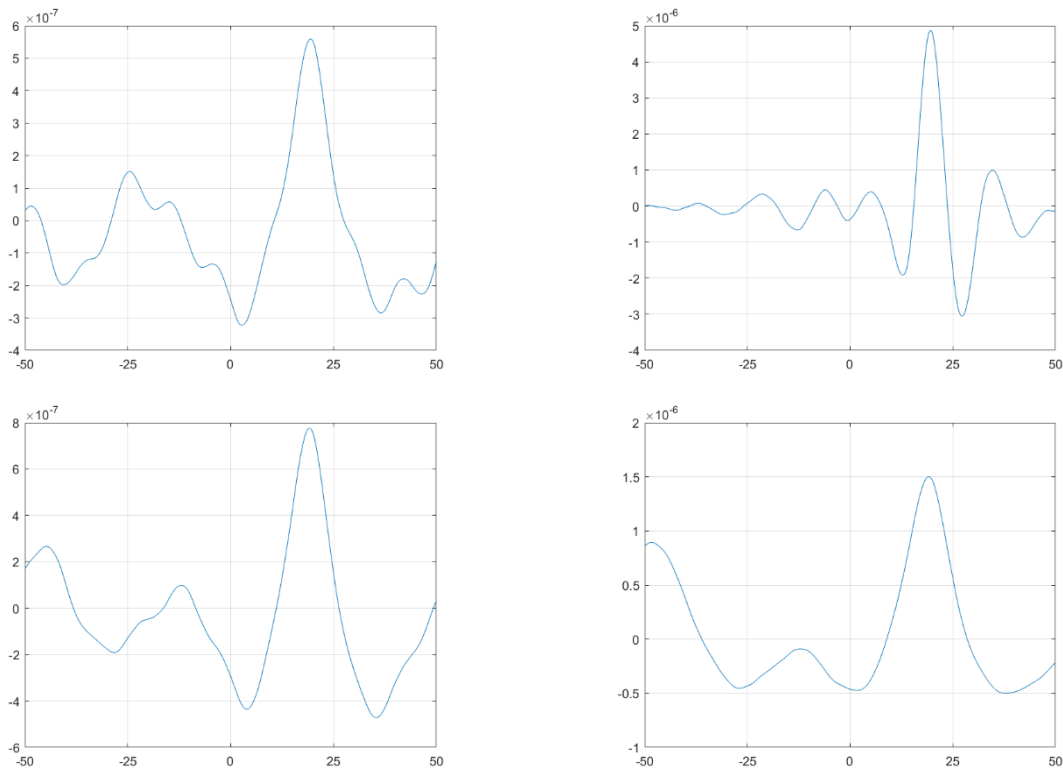


Figure 5. Cross-correlation between two vertical geophones at 18m depth in two separate holes 50m apart: Core-break (upper left panel), Rod Drop (upper right panel) and seismic while drilling. The drill bit was at approximately the same depth and a further 50m away and in-line with the other two holes. The inferred travel-time from the peak correlation is 19.7 +/- 0.1 ms for all three types of acquisition, which corresponds to S-wave first arrival time.

After performing cross-correlation of various geophone pairs with drilling at a depth that is line with the geophone pair it seems arrival times seem repeatable and precise with different methodologies (drilling, rod-drop, core-break) to 0.1 to 0.2 ms. This precision is important as the difference in arrival time between one sensor level and another is

only about 0.35 ms at 5000 m/s velocity. The S-wave velocities were between 2,700 and 3,300 and were more forgiving of our travel-time measurement precision.

The baseline ZVSP data gathered, and a nearby acoustic log, indicates that the S-wave tomograph will not be uniformly bland. The lowest part of the holes (at about 35-40m has quicker (by 10 to 20%, 3400m/s vs 2900 for the upper portion) velocities. Our ability to detect lateral changes between holes is limited by sensor distribution and spacing with the 50m borehole depth and separation. Nonetheless we performed a tomography inversion with customised inversion code (Figure 6). We do not see higher velocities the ZVSP data at these depths because it is slightly deeper than 35 meters and the cross-hole waves should refract slightly to one side out of plane (up-dip). The limited resolution in timing waves over 10m makes the ZVSP check data rather than precision reference in any case. Regardless, the tomogram and resulting travel times are generally as anticipated from our knowledge of the geology and cross-check ZVSP measurements.

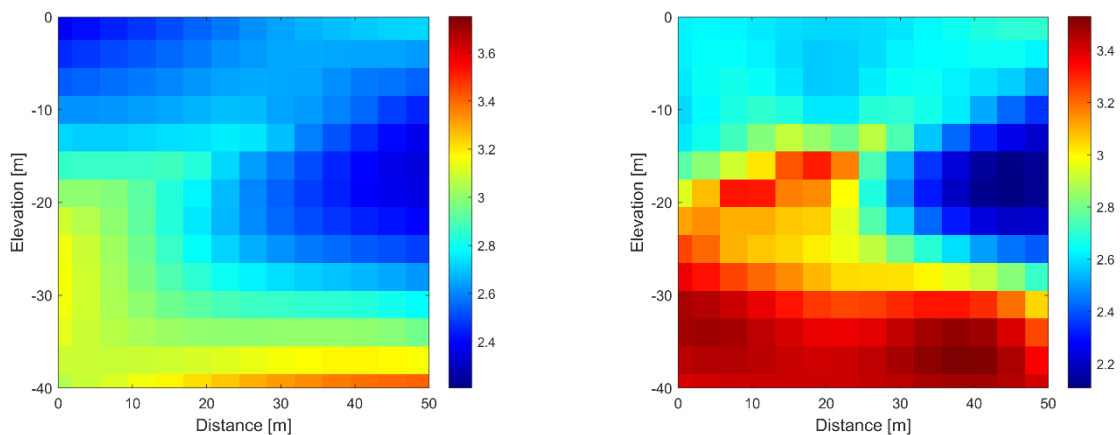


Figure 6. Tomogram with different weights on petrophysical constraints (left panel – velocity not strongly clustered; right panel – data strongly clustered) from inferred S-wave travel times between hole CBHT06 (left) to CBHT07(right) 50m apart from “illumination” by a drilling in CBHT08 (50 to 100m from the sensors strings). There is an anomalous zone near CBHT06 at depths of approximately 25-30m that appears strongly influenced by one data point; however, there could be some local change in dip-plunge or offsets from an unknown fault. The overall trend and the S-wave velocity values agree with other data and the known physical properties of the geology.

CONCLUSIONS

Despite challenges, seismic while drilling with diamond drill rigs in conjunction with geophone sensor arrays is feasible and should provide every useful life-of-mine data. We have developed a methodology and instruments that allow the drillers to install and even collect tomography data. The in-line configuration of drill-rig and two instrumented boreholes is a viable means to perform cross-well. tomography. Our initial work found that S-wave energy to be predominant. S-waves should provide higher spatial resolution in tomography: a serendipitous outcome in our work.

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