The application of VSP in the Pilbara

Ashley Grant *
BHP Minerals Australia
Perth, Australia
Ashley.Grant@bhpbilliton.com

Tim Dean
Department of Exploration
Geophysics
Curtin University
tim.dean@curtin.edu.au

Huw Rossiter
Kinetic Group
Perth, Australia
Huw.Rossiter@kinetic.group

Brenton Armitage
Kinetic Group
Perth, Australia
Brenton.Armitage@kinetic.group

SUMMARY

The construction of geological and geotechnical models in typical Pilbara iron ore environments is vital to enable an optimized mine design for the life of the asset, while maintaining pit wall integrity and overall mine safety. Geotechnical assessments require the measurement of geomechanical properties, such as the triaxial shear, direct shear and unconfined compressive strength tests and pressure and shear wave velocities on diamond core samples. Ideally, these velocities would be measured in Reverse Circulation (RC) boreholes as their spatial density is far higher than diamond drilled holes. Unfortunately, despite its value, such data is seldom collected as a large proportion of the holes are above the water table, limiting the use of sonic-logging tools. Even if measurements are possible, damage to the borehole caused by drilling biases the resulting velocity measurements.

This paper details the results of a trial using the vertical seismic profile method to directly measure in-situ seismic velocities in RC boreholes. The method was successful in determining the velocities of the formations through the entire length of the holes. The data in several boreholes was of sufficient quality for the application of more advanced processing methods, important for geological mapping and the processing and interpretation of surface seismic data.

The success of this first trial has implications for future iron-ore developments in the Pilbara. The widespread acquisition of accurate seismic velocity data is likely to enable the creation of more accurate geotechnical models and could improve future development decisions.

Key words: VSP, ZVSP, UCS

INTRODUCTION

The importance of gathering geomechanical data to aid in the mine design and planning process including the assessment of pit wall slope stability is acknowledged by many researchers (e.g. Kozyrev et al., 2015). As shown in Figure 1, there is clear relationship between lab-based porosity and ultra-sonic velocity measurements and Uniaxial Compressive Strength (UCS); many researchers (e.g. Entwisle et al., 2005) have demonstrated this. Acquiring reliable porosity measurements in the Pilbara is another area of active research (Maldonado, et.al, 2017).
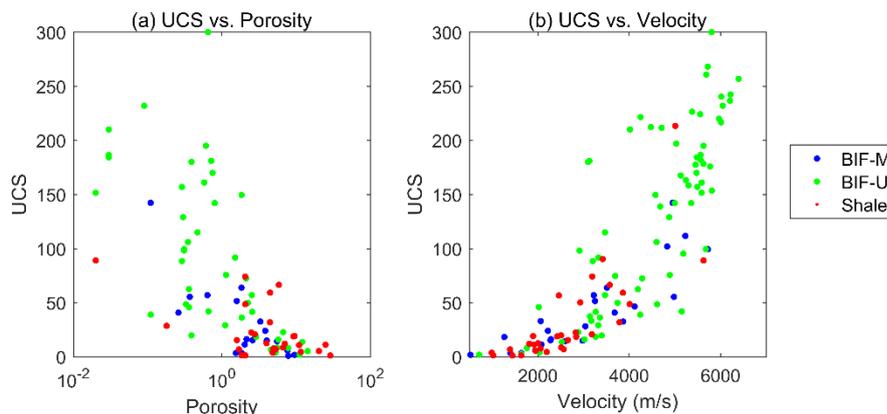
Figure 1: The relationship between uniaxial compressive strength and porosity and p-wave velocity.

UCS is primarily used to differentiate materials based on their compressive strength where soils or highly weathered rocks (<1MPa) behave differently to competent rocks (>1MPa). Along with a simple scaling factor (Hoek, 1983), UCS data is used in a variety of geotechnical assessments including slope stability studies.

Currently, the primary method for gathering velocity data is through the testing of core samples. Core sample testing obviously depends on the availability of samples and is relatively expensive and time consuming, it also produces results that differ from properties measured of the rock in-situ (Chalupa, 2012). In the Pilbara, relatively few core holes are drilled due to their high cost when compared to other drilling methods such as reverse circulation (RC), resulting in sparse datasets. Even when drilled the friable nature of many of the local formations often results in core loss or fractured core samples that are not suitable for testing. Thus the limited number of competent samples that are available for testing has the potential to bias models. Ideally an in-situ method of determining geomechanical properties in RC drill holes should be used. In the petroleum industry, these properties are routinely calculated using downhole geophysical density and sonic logs. Unfortunately, this is not possible in the Pilbara because of the challenges of undertaking sonic measurements. Specifically, sonic tools require the hole to be filled with fluid, and RC hole conditions in friable formations can result in very poor data quality resulting from the rugosity of the drill hole walls (see Figure 2). In addition, the smaller holes and tighter budgets in the mining industry when compared to the petroleum industry mean the sonic tools employed are smaller, have a lower signal to noise ratio and are limited to compressional and faster than fluid shear measurements.
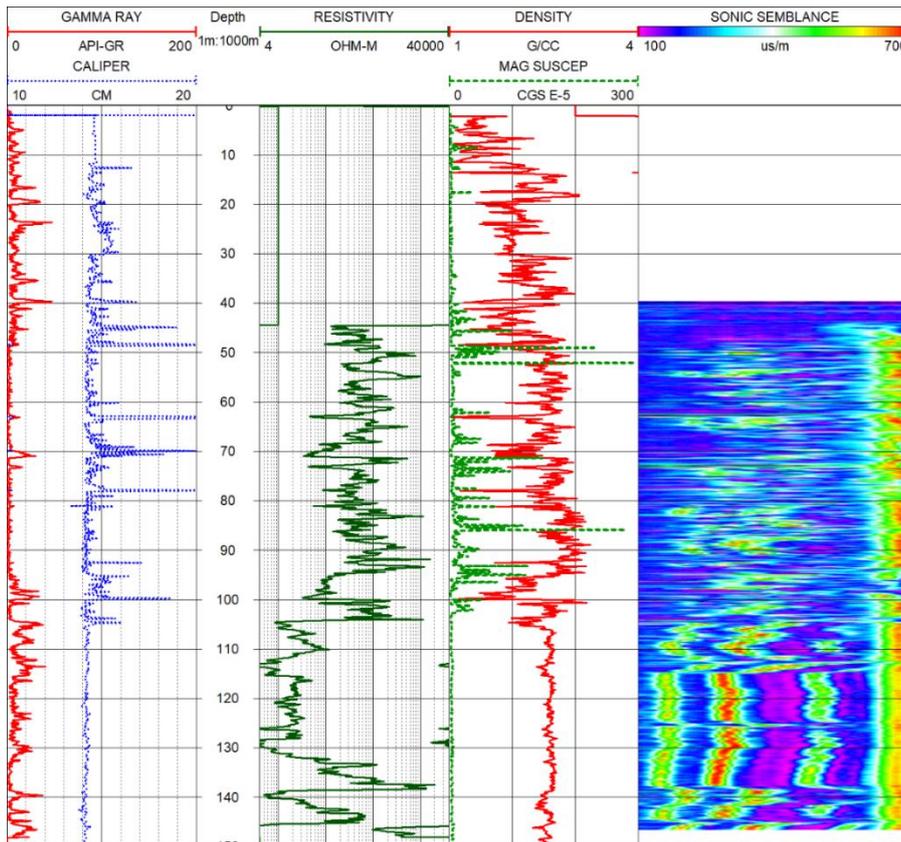
Figure 3: A typical downhole geophysical dataset recoded in the Pilbara. Note the strong arrivals in the competent formation from 115 to 150m, but the weak and inconsistent signals in the more friable formations above 115m. Note the calliper signifying rugose hole conditions in the upper part of the hole and the water level at around 44m.

An alternate method for gathering in-situ compressional and shear velocity data is to acquire a Vertical Seismic Profile (VSP) survey. A VSP involves deploying vibration sensors (typically geophones) down a hole (Figure 4). The sensors are typically contained within a metal tube or sonde that is mechanically clamped to the borehole wall. The sensors record the passage of shock waves through the earth generated by a source at the surface. By deploying the sensors at different depths and measuring the time taken for the energy to travel downhole, a detailed velocity function can be generated. Figure 5 is an example of a synthetic VSP record generated using a geological model with steadily increasing velocities (Figure 5a). As the velocity increases the travel-time for the down-going wave decreases (i.e. the gradient of the first-arrival on the t-x plot, Figure 5b, increases). Up-going waves, or reflections, can also be seen being generated at each interface, the position of the generating interface being the intersection of the each reflection and the down-going wave.
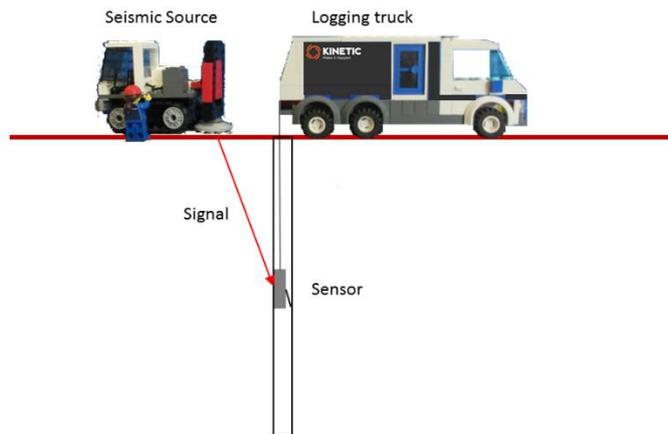
Figure 4: Simplified diagram of VSP acquisition.
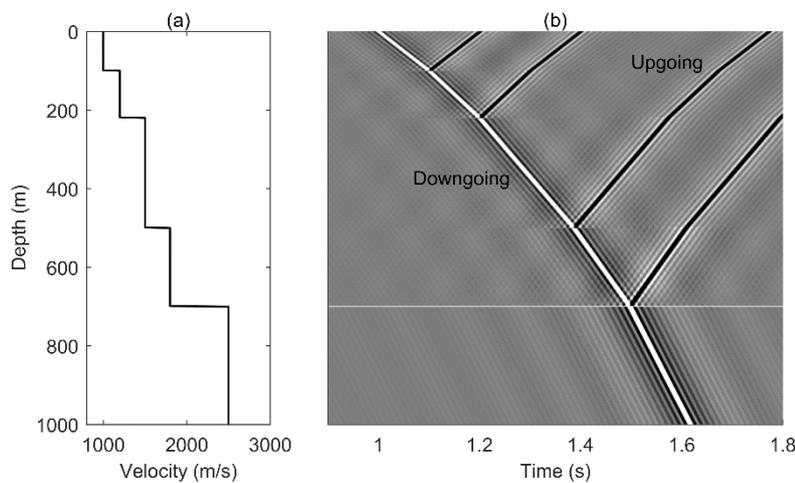
Figure 5: Synthetic VSP record. The down-going and up-going (reflected) wavefields are labelled on (b).

If data quality is sufficient then the data can be further processed to generate a corridor stack. This process is illustrated using a different synthetic dataset in Figure 6. The raw data (Figure 6a) clearly shows a series of reflections. By picking the first-arrivals we can calculate the interval velocities, and through the application of a median filter we can then separate the down-going and up-going wavefields (Figure 6b). We can then flatten these reflections and transform them into two-way time (i.e. as if the reflection were recorded at the surface), Figure 6c. Finally we sum the traces to generate a corridor stack (Figure 6d) which can be used in the processing and interpretation of surface seismic data. The corridor stack can also be plotted against depth (using the velocities derived in the first stage of processing) allowing the identification of the major interfaces as shown in Figure 6e.
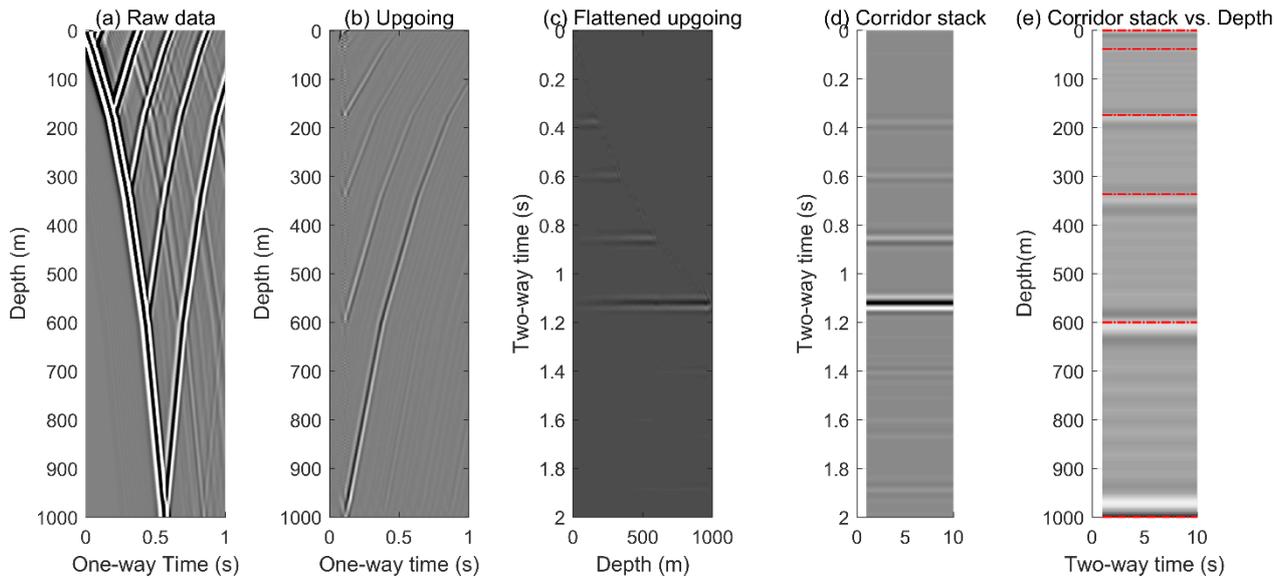
Figure 6: Modelled data at various stages in processing. The red lines on (e) indicate the actual depths of the interfaces in the model.

Although sonic and VSP derived velocities can vary slightly, principally due to the different operating frequencies (5 to 25kHz vs. 10 to 150 Hz for the VSP) and the volume of rock interrogated, the sonic log is limited to sampling the rocks less than 0.3 m from the borehole whereas the seismic waves encompass a region of more than 10 m (Stewart et al., 1984), they are generally consistent. The larger sampling regions implies that the VSP derived velocity is likely to be the more representative, particularly if the drilling has altered the nature of the borehole wall.

Given the difficulties in acquiring sonic data in the challenging conditions in the Pilbara, and the success of acquiring VSP data in other environments, it was decided to run a trial to determine the feasibility of acquiring velocity data using a VSP survey. If successful, the lessons learned from the initial trial could be used for future surveys, possibly using more complex acquisition geometries such as walk-away surveys, enabling the creation of 2D or even 3D models.

METHOD

The trial was conducted using a zero-offset (or check-shot) geometry where the source was placed between 2 and 4 m of the hole containing the sonde. The sonde contained a 3-component geophone as well as a hydrophone and was run on a standard 4-core wireline cable. The seismic signal was generated using a customised weight drop. The recording system was triggered using a piezoelectric trigger attached to the source baseplate. Data was recorded at either 1 or 2 m intervals with between five and eight shots recorded at each depth. Data was acquired from a total of eighteen holes (with one repeat run) up to a maximum depth of 250m.

A standard VSP processing flow was applied to the data, specifically first-break picking; velocity calculation and smoothing; separation of up-going and down-going wavefields using a median filter; exponential gain; mute; and corridor stack. Although the latter processing stages could only be applied to the better quality datasets, velocity data from at least the initial depths, and often across the full depth range, could be determined (Table 1). The maximum depth with useable data was 150 m.

Table 1. A summary of the datasets acquired during the initial test.

Index	Raw Data quality	Proc. Data quality	P-velocities	Approx. max. depth (m)
1	Good	Excellent	Full	80
2	Excellent	Excellent	Full	80
3	Good	Good	To 45 m	80
4	Good	Good	Full	80
5	Good	Good	Full	90
6	Excellent	Excellent	Full	110
7	Excellent	Excellent	Full	60
8	Good	Excellent	To 70 m	80
9	Poor	Excellent	Full	90
10	Poor	Good	To 80 m	110
11	Poor	Poor	To 25 m	110
12	Poor	Poor	To 35 m	150
13	Good	Good	To 150 m	250

14	Excellent	Excellent	Full	100
15	Good	Excellent	Full	70
16	Poor	Good	To 55 m	70
17	Poor	Good	To 110 m	140
18	Poor	Good	To 110 m	140

RESULTS

An example of the raw data and the extracted velocity profile is shown in Figure 7. The data quality in this case was 'excellent' and multiple up-going reflections are clearly visible.
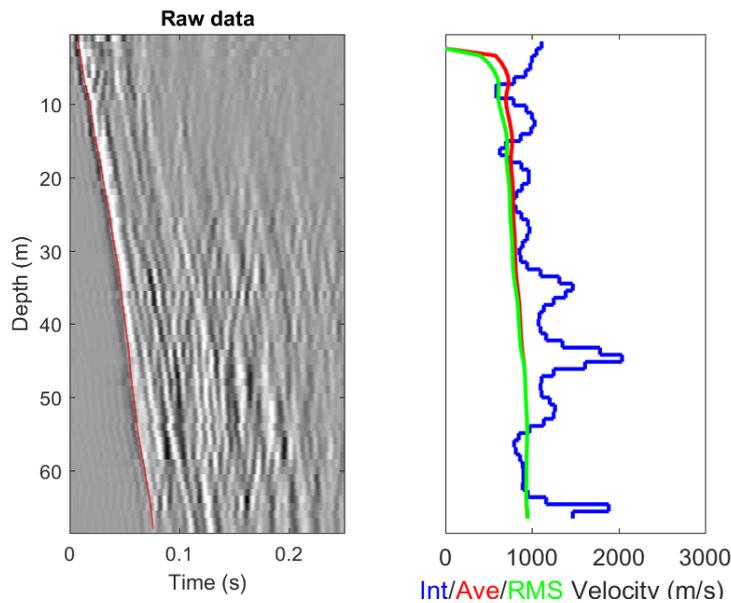
Figure 7: (left) raw data and (right) extracted velocity profiles. Multiple reflections can be seen on the raw data (events going from the bottom left to the top right of the plot). The average velocity is each depth divided by the time taken to reach that depth from the surface ($\sum_{i=1}^{n} V_i t_i / \sum_{i=1}^{n} t_i$). RMS velocity is given by $\sqrt{\sum_{i=1}^{n} v_i^2 t_i / \sum_{i=1}^{n} t_i}$.

Figure 8 shows another dataset which has been processed through to corridor stack resulting in the identification of several strong reflectors. Even if the data is not of sufficient quality for corridor stacking we can use the first-break picks to identify layers in a manner similar to seismic refraction processing. An example of the procedure is shown in Figure 9; starting with the raw first-break picks (the green dots on the left hand panel) we identify sections with relatively constant velocity and fit straight lines to them (the red lines). The intersection of these lines indicates the intersection of layers with different velocities. The resulting interval velocities are shown on the right-hand panel in Figure 9 and show good agreement with the interpreted stratigraphy indicated by the different colours.
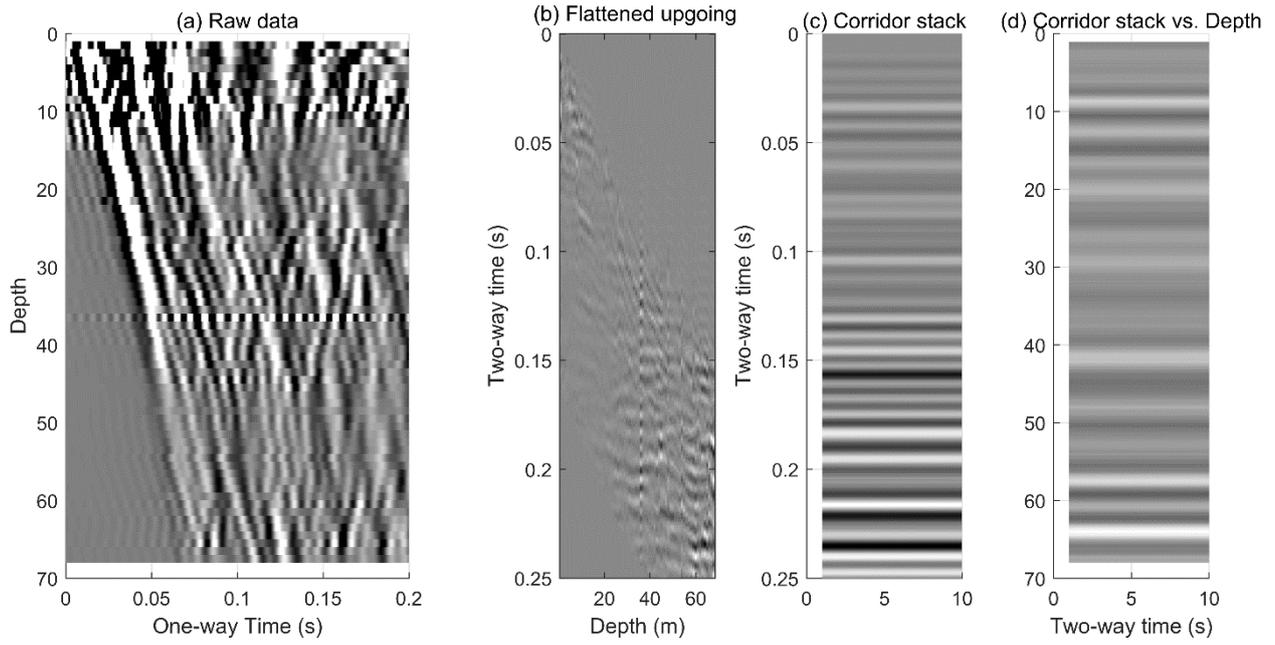
Figure 8: An example of data that has been processed through to corridor stack. Note that the flattened up-going events are shown prior to the application of the mute.
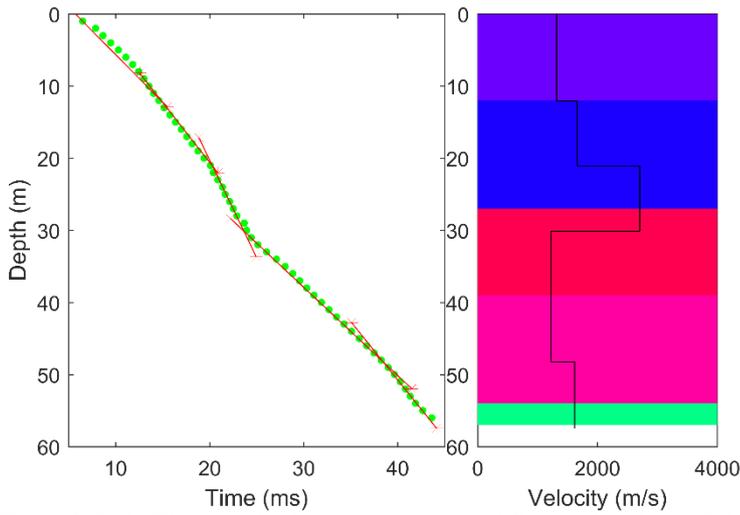
Figure 9: Left: First-break picks (green dots) and fitted velocities (red lines). Right: Resulting interval velocities overlain on the logged geology.

DISCUSSION AND CONCLUSIONS

The results from this test showed that VSP data can be successfully acquired in RC holes in the Pilbara. The data quality was sufficient to calculate interval velocities in all the holes but not necessarily over the full depth (Table 1). Depth penetration can be improved through the use of a higher-energy source and the stacking of additional records (as well as the exclusion of bad shots from the stack, an ability which was not offered by the acquisition system employed for this test). In several holes data quality was sufficient to allow the generation of corridor stacks enabling the identification of several reflectors. Even in holes where corridor stacks were not achievable interfaces could be identified by applying refraction-style processing (Figure 9).

As detailed in Dean et al. (2016), calculating interval velocities for very small depth intervals (typically intervals are of the order of 10 to 20 m) is difficult as very small differences in time picks results in large velocity fluctuations (in the results shown here the velocities had to be smoothed). Some of these differences are due to variation in the source timing, for future surveys multiple-sondes should be used with their spacing equal to the required depth interval; this would negate any source-related timing issues. Using multiple-sondes will also increase the efficiency of the survey.

Direct comparisons between VSP derived velocities and UCS measurements were not possible in this case as only two geotechnical dedicated diamond holes were logged as part of the trial (whose primary objective was to determine the feasibility of VSP acquisition in RC holes). From these two diamond holes, only core six samples were sent to the lab for UCS testing, and only four of these were adequate for testing. This further illustrates the difficulty in making unbiased (i.e. results are not skewed by the restriction to samples that are consolidated enough to enable measurements to be made) geotechnical measurements even when expensive diamond core is available.

Planned future work on this dataset involves combining the data from all the holes to examine the relationship between velocity and geology, ideally in combination with other logging data. Given the success of this program, future acquisition is currently being planned and will involve both an improved source and acquisition system to address some of the shortcomings identified in this test (Dean et al., 2018).

Routine VSP velocity measurements could potentially reduce the amount of diamond core drilling required in the geotechnical assessment for open pit mine designs.

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