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Petroleum-based downhole geophysical methods for subsurface characterisation: a case study from Cadia East mine

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Abstract

Subsurface characterisation in underground mining is often limited to interpretation of drillhole cored data and surface geophysical data, later aided by geological mapping of limited underground development. Due to the large volume and increasing depth of orebodies in block cave mining, subsurface characterisation is increasingly reliant on 3D modelling from spatial sampled core data. This paper presents a case study from the Cadia East block cave mine, where a series of petroleum-inspired techniques were used to: (i) enhance subsurface characterisation with continuous imaging at depth; and (ii) to decrease the risks associated with interpretation of sparse geophysical data. A comprehensive suite of wireline logging was acquired in one drillhole and included full bore formation micro-imager, sonic logging and vertical seismic profiling (VSP). The formation micro-imager data were used to identify the fault and fractures that cross the wellbore. These data were also used in conjunction with sonic data to generate a 1D Mechanical Earth Model (MEM) as well as a high resolution Unconfined Compressive Strength (UCS) profile. In addition to the drillhole-centric characterisation, VSP measurements extended the characterisation away from the wellbore. The VSP acquisition comprised two source locations allowing measurement of compressional, shear velocities and attenuation as well as seismic imaging of the eastern end of the orebody. The short VSP-derived 2D seismic line showed presence of several geological structures, further validated with the integration of the micro-imager data. This added a significant amount of confidence to the structural/geotechnical model. It is envisaged that through the application of petroleum-based geophysical methods, additional information can be obtained such that geotechnical hazards are incorporated into long-term mine planning as early as possible.

Keywords: *Cadia East Mine, vertical seismic profiling, formation micro-imager*

1 Introduction

Subsurface characterisation plays a key role in the design of a block cave mine, affecting decisions such as the placement of critical infrastructure and safety aspects. The ever-increasing depth of block cave mines means that geotechnical work is reliant on 3D modelling from coarsely sampled core data integrated with surface geophysical data. In the petroleum industry, such practices are common with advanced levels of integration of borehole data with surface geophysics. In this paper we present a case study from the Cadia East block cave mine, where several petroleum techniques are applied to a hard rock mining environment.

The Cadia Valley Operations (CVO) is Australia's top-producing gold mine and comprises Cadia East with several macroblocks using the block caving mining method (Figure 1), with ore extracted and processed from a network of underground tunnels extending over many tens of kilometres. Underground construction of critical infrastructure is time-consuming and heavily relies on in-depth understanding of geological structure. Some structures, such as faults, associated fracture zones, dykes and other lithological contacts, can be the source of geohazards. The current methodology to reduce risks associated with geohazards involves the identification of hazardous structures by integration and interpretation of in-mine geological mapping data and significant amounts of core drilling and logging data. Exploration drilling targets the orebody volume and geological structure information in areas surrounding the orebody is often lacking and core drilling is expensive.

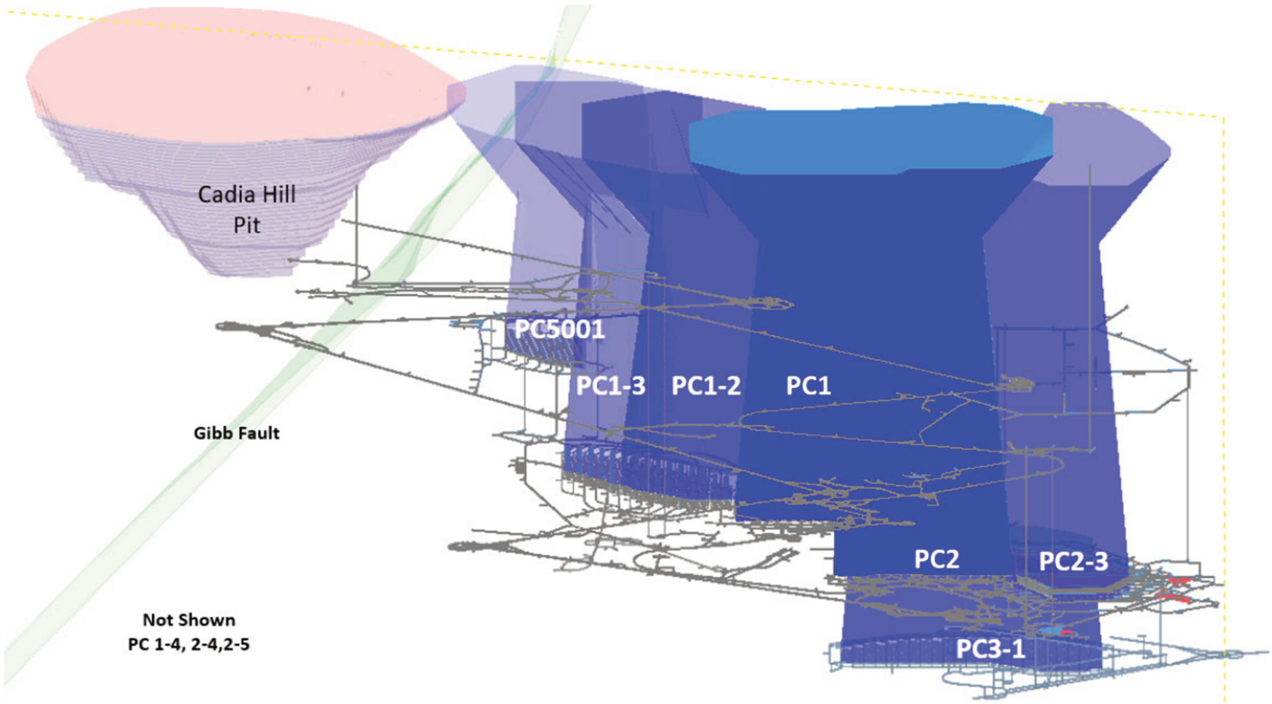

Figure 1 Layout of the Cadia East block cave (current: solid blue; planned: translucid blue) and associated infrastructure

A pilot study to assess whether more economic petroleum industry techniques can be used in hard rock mining to reduce the reliance on more costly conventional mapping and core logging techniques has been undertaken at the Cadia East PC2–3 cave expansion project. Petroleum well logging is geared for sedimentary environments and hence only a select few techniques can be directly translated to mining. Of these, sonic logging, wellbore imaging and borehole seismic imaging are the most applicable as they provide the basic information regarding geological structure and rock strength. The former is a key input into a 1D Mechanical Earth Model (MEM) that is used to compute a log of Unconfined Compressive Strength (UCS) (Lewis et al. 2021).

2 Methodology

Petroleum-style wireline drillhole logging was performed by a service company in two descents in RE006, a near-vertical PQ-size drillhole located in the vicinity of the PC2–3 cave. The first run contained a combination of the gamma ray tool, a sonic logging tool and the full bore formation micro-imaging tool. The second run contained a gamma ray tool and eight versatile seismic imaging shuttles that were used to record two vertical seismic profiles (VSP).

2.1 Vertical seismic profiling

The objective of VSP is to measure the vertical compressional and shear velocities, attenuation profiles and generation of a small seismic image across the eastern end of the block cave. This is achieved by two types of VSP surveys respectively: a zero-offset VSP (ZVSP, also referred to as rig-source VSP) for velocity and attenuation measurement, and an offset VSP (OVSP) for imaging (Figure 2).

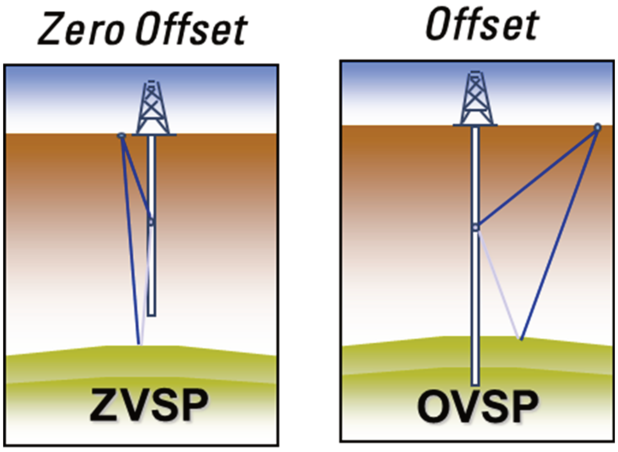

Figure 2 Schematic of the two types of VSP surveys acquired at Cadia East

VSP surveys are commonly used in petroleum industry, providing key input parameters (velocity and attenuation) to surface seismic processing or high-resolution VSP images in complex geologies. In mining, surface seismic surveys have been in increasing demand for deep exploration (Malehmir et al. 2012). However, high costs and low reflectivity have prohibited surface seismic from becoming commonplace. In contrast to surface seismic, ZVSPs and OVSPs have been touted as more accessible alternatives that require less surface access, are cheaper and quicker to acquire, and provide high resolution. ZVSPs have been used to compute attenuation profiles at Kambalda (Pevzner et al. 2013) as well as imaging in deviated drillholes (Greenwood et al. 2012). OVSPs have been used to image structure of a sulphide deposit at Kylylahti (Riedel et al. 2018). This paper shows application of these methods to a porphyry gold-copper deposit at Cadia.

The setup at the test site, as well as the map showing the well location and source locations are shown in Figure 3. Both types of surveys require a single source location for each survey, reducing access challenges.

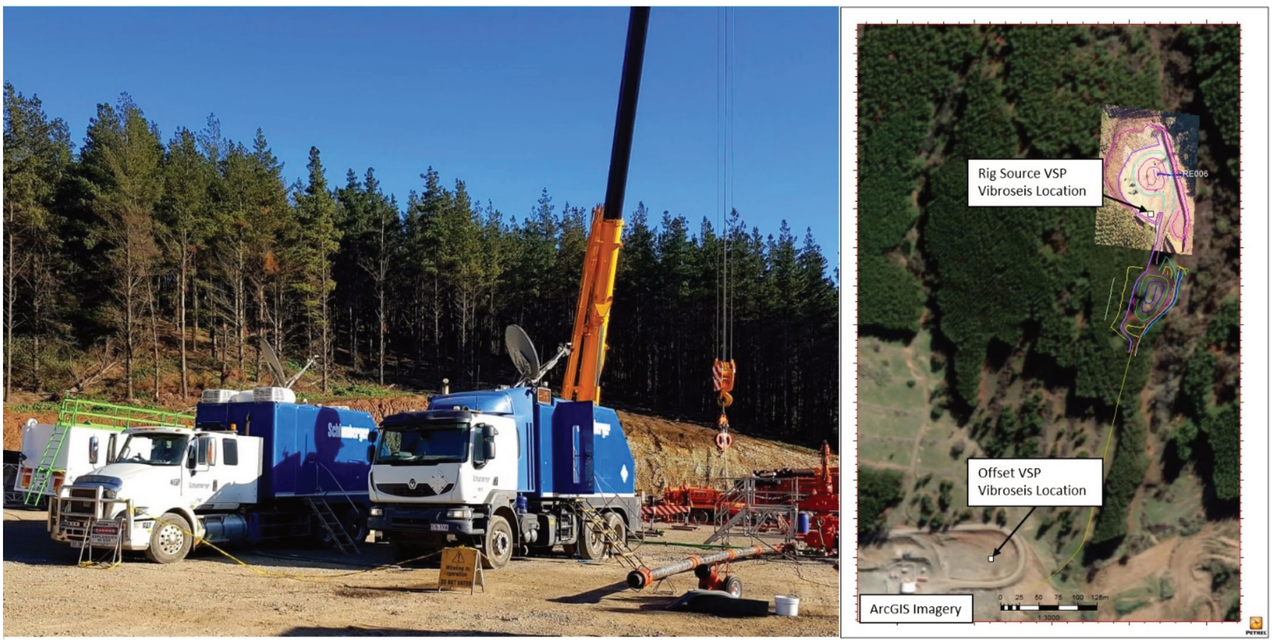

Figure 3 Surface setup for acquisition of VSP surveys and a map showing source locations

In both cases the downhole seismic antenna comprises eight triaxial accelerometers, that record the acceleration of ground motion at their location, which are spaced every 15.12 m. Each accelerometer has a calliper arm, ensuring good coupling between the rock mass and the tool. The overall length of the seismic antenna is 105.8 m whilst the full array, together with the gamma ray tool, is 130.82 m. The seismic array was deployed using a crane (Figure 3). The acquisition began near the maximum depth of the RE006 drillhole.

As the length of the drillhole is larger than the length of the sensing array, the experiment is repeated after the downhole array is moved approximately 121 m. Complete wellbore coverage is achieved by starting at the bottom of the drillhole and finishing near the surface, which took 5 hours 45 minutes for the ZVSP and another 5 hours 30 minutes for the OVSP. The major difference between the two types of surveys is the location of the seismic source. However, the seismic source itself is the same: a small vibroseis unit that has a 7.4 T weight with a reaction mass of 680 kg. This vibroseis unit produces a 12 second-long linear 10 to 150 Hz sweep.

2.1.1 Zero offset VSP

For the zero-offset VSP, the seismic source was located 49.4 m away from the drillhole flange at 255° N azimuth. The data were acquired in 13 settings of the eight-level tool (Figure 4).

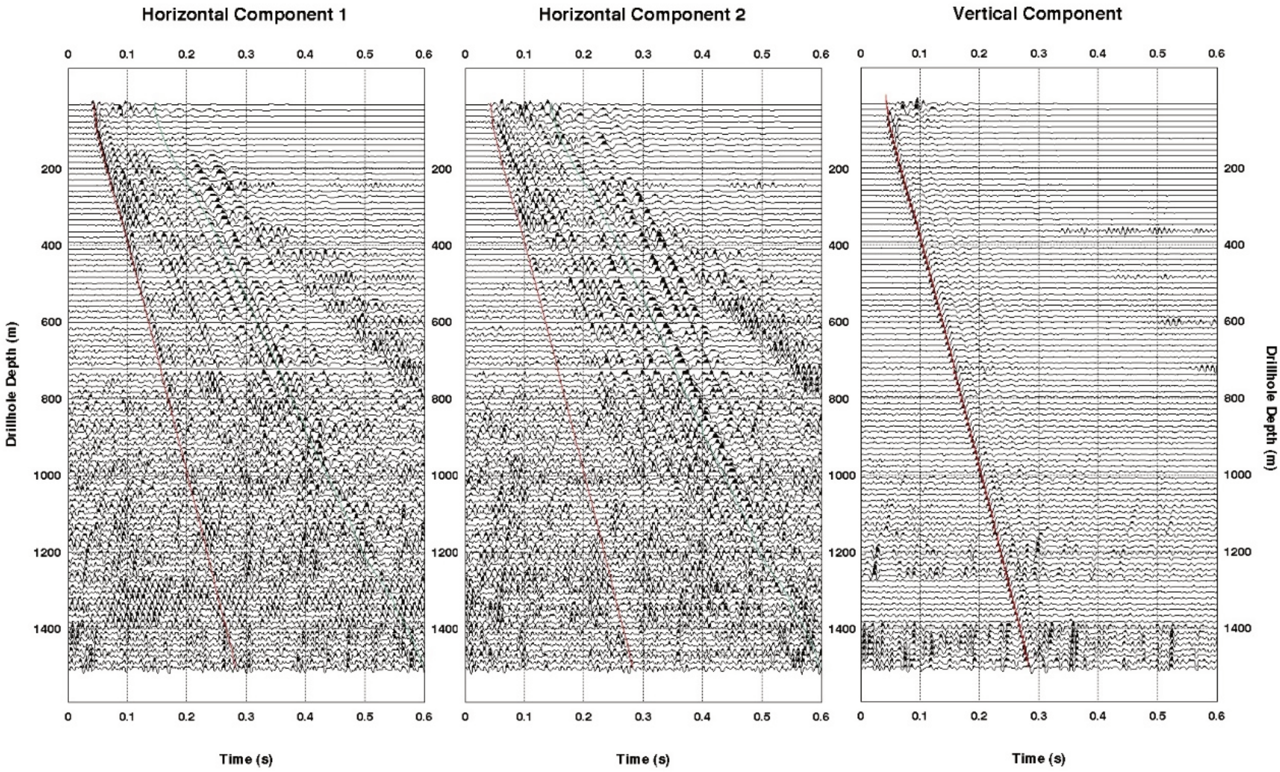

Figure 4 Raw zero-offset VSP data. Source positioned 49.4 m away from surface flange of the drillhole

Conventional VSP processing (Hardage 1985) was carried out using the vertical component only to derive velocity profiles and the seismic trace at the RE006 drillhole. Table 1 shows the set of parameters used for this survey. In addition to this, a multi-spectral Q estimation methodology (Leaney 1999) was applied to the data to derive the attenuation profile (where the attenuation parameter Q is inversely proportional to attenuation). The full set of data extracted from this survey is shown in Figure 5.

Table 1 VSP processing parameters

Type of process	Key parameter
Normalisation	100 m around first break for ZVSP N/A for OVSP
Wavefield separation	ZVSP: Velocity Filters 7-level for downgoing, 5-level for upgoing OVSP: Parametric wavefield separation, 10 to 150 Hz range, 1 s windows
Deconvolution	Trace-by-trace, 10 to 150 Hz
Enhancement	ZVSP and OVSP: Velocity Filter: 5-level for upgoing
Stacking	ZVSP: 100 ms from the first break
Migration	OVSP: Generalised radon transform migration (model based), 1 degree aperture

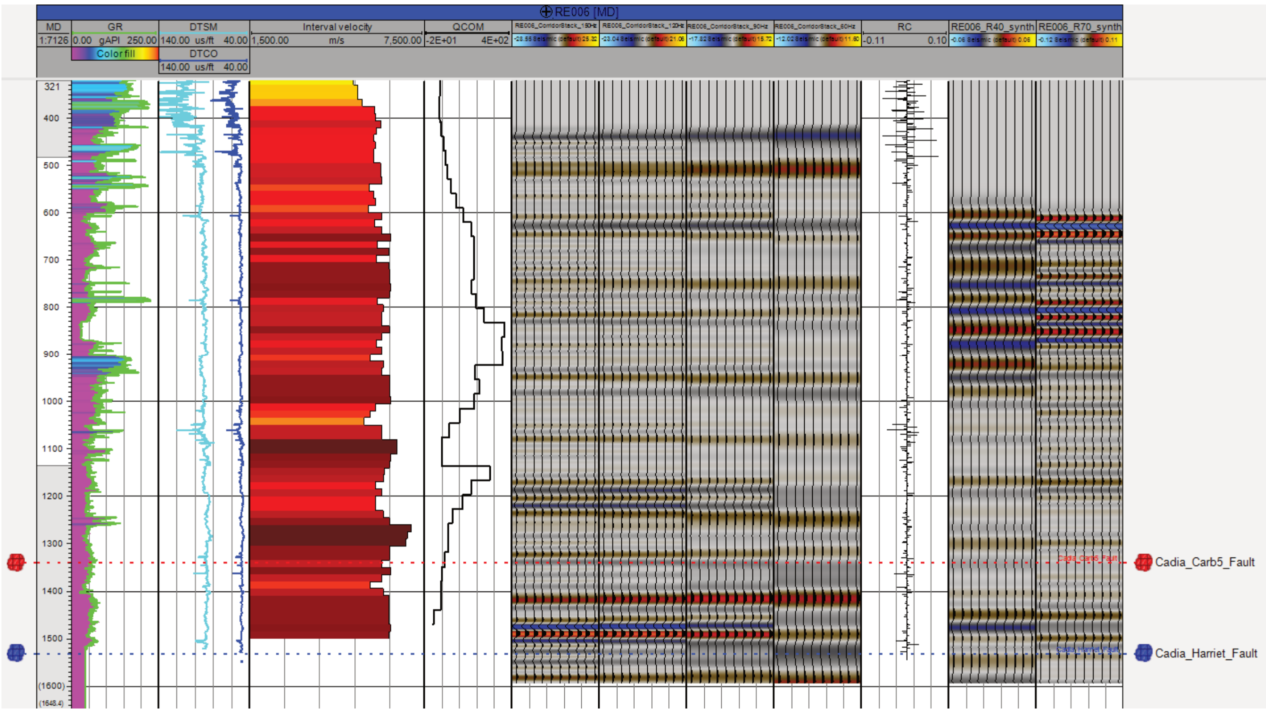

Figure 5 Zero-offset VSP processing result. The tracks contain Gamma Ray in green (coloured in), shear sonic (cyan), compressional sonic (navy), interval velocity in black (coloured in), Q (compressional attenuation curve) in thick black, VSP corridor stack (10 to 150 Hz range), VSP corridor stack (10 to 120 Hz range), VSP corridor stack (10 to 90 Hz range), VSP corridor stack (10 to 60 Hz range), reflectivity curve computed from sonic, 40 Hz zero phase Ricker synthetic, 70 Hz zero phase Ricker synthetic. Measured depth where two identified faults cross the drillhole are indicated by read and blue dashed horizontal lines

The zero-offset VSP has shown that the compressional seismic velocity is near-constant below 400 m from surface. This is consistent with known geological changes. However, the attenuation of compressional energy measured by the ZVSP is significantly more than previously documented. The incumbent measurement (Q = 720) was from analysis of data acquired by the in-mine seismic monitoring array. The VSP enabled us to compute a profile that is changing with depth and showed that on average, attenuation is much higher than originally estimated in this area, Q = 170 in the 10 to 150 Hz range.

2.1.2 *Offset VSP*

The offset VSP (OVSP) source was located 558 m away at 245° N from the drillhole flange (Figure 3). The data were also acquired in 13 settings (Figure 6).

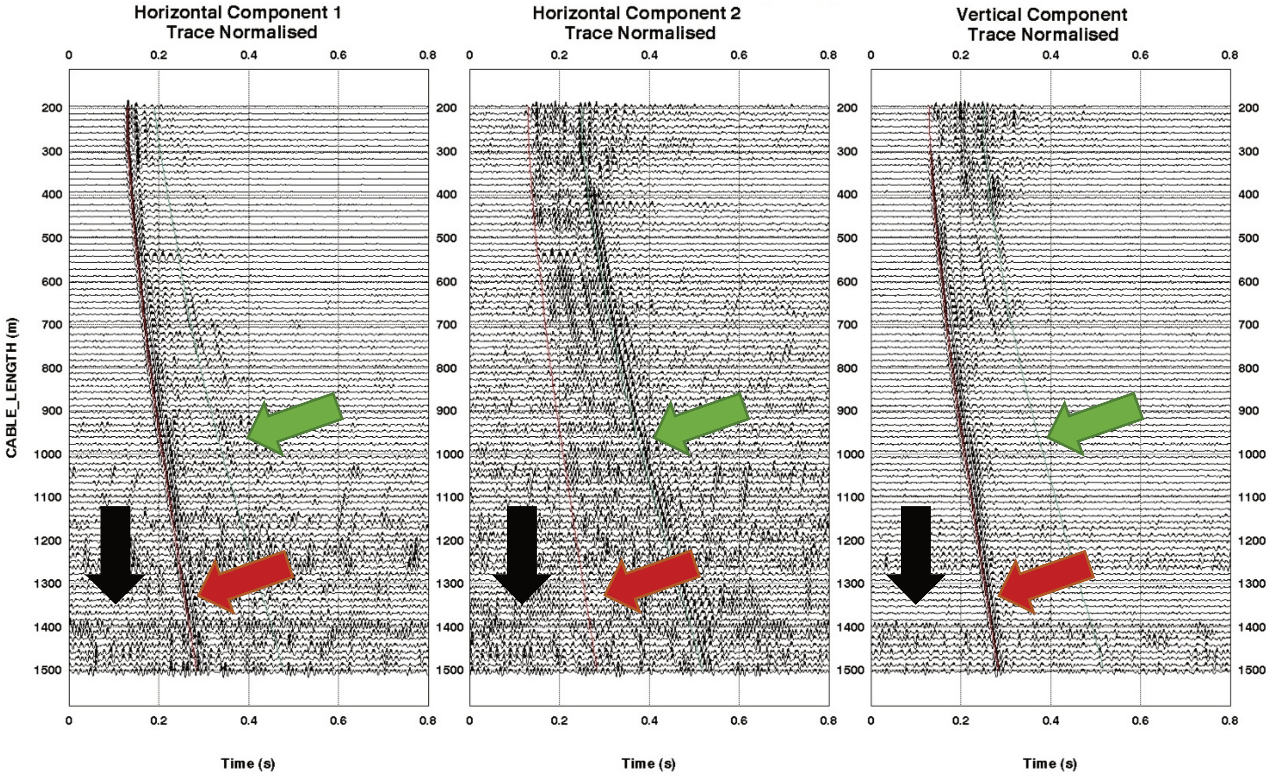

Figure 6 Raw OVSP data. The red line shows the first break of the seismic energy (also annotated by red arrow), and the shear arrival is annotated by the green line (and highlighted by green arrow). Note the anthropogenic noise (annotated by black arrow) from block cave mining activities before the first compressional break

Due to a source offset, the presence of shear energy was observed in the OVSP data and this enabled us to measure the shear velocity as a function of depth. The parametric wavefield separation technique was used (Leaney 1990) to derive a scalar upgoing compressional wavefield. The full set of processing parameters is shown in Table 1. The final step in processing was migration of the data using a generalised radon transform approach (Schneider 1978; Miller et al. 1987) to derive a small seismic image in the direction of the seismic source (Figure 7).

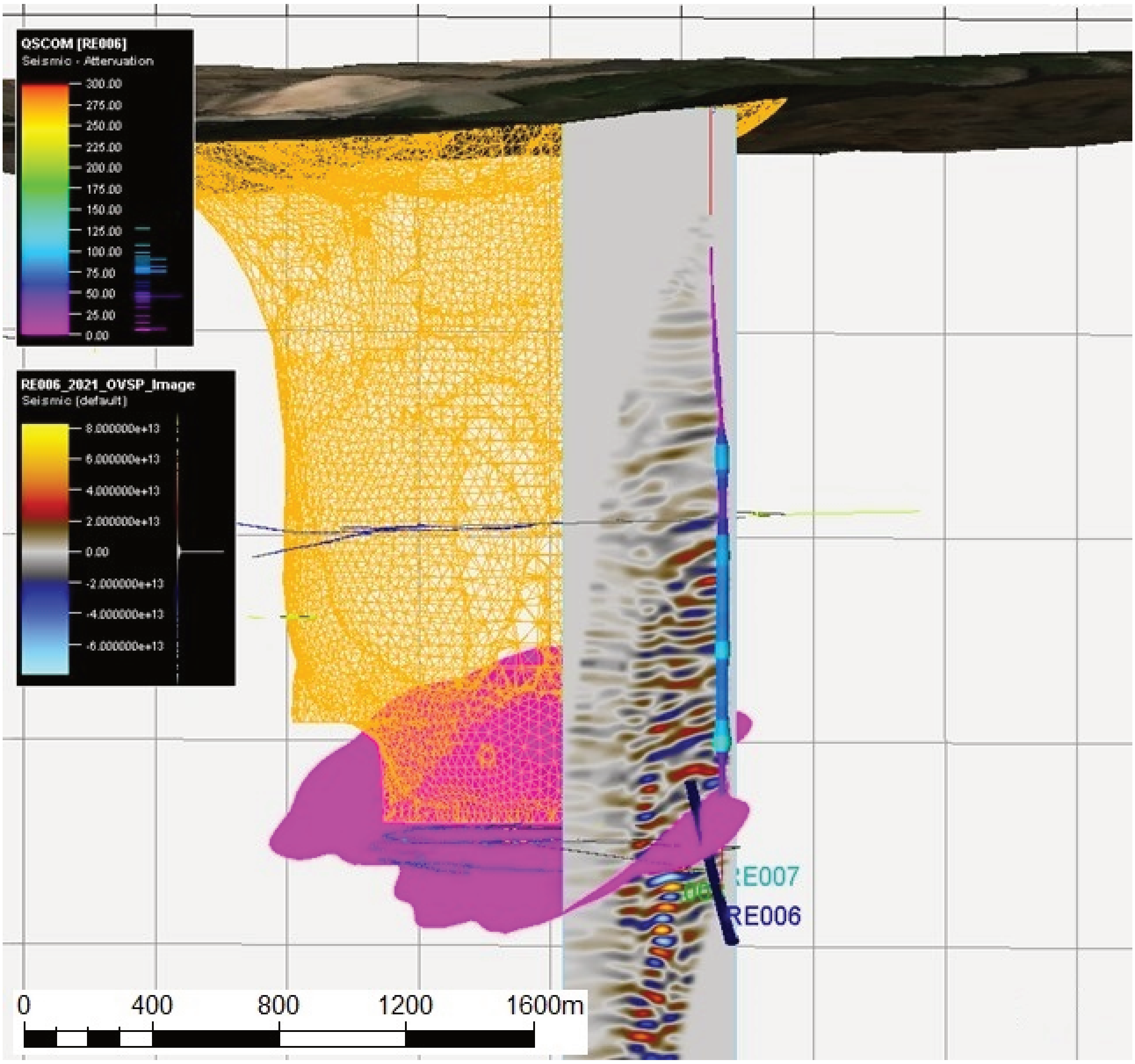

Figure 7 Migrated OVSP processing result (shown in a 3D view). Also shown is the block cave (yellow wireframe), development drives (blue lines), as well as two known faults (magenta and blue planes). The RE006 wellbore is highlighted with a Shear Attenuation (Qs) curve. The vertical bars are 400 m apart

The derived seismic image is 360 m long and is located at the eastern end of the block cave expansion. It shows several geological features that are best interpretated together with information from the wellbore imaging tool as well as ‘a priori’ geological models. In addition to the seismic image, because of the presence of strong shear energy, a profile of shear wave attenuation could be derived using multi-spectral techniques. It was found that the shear wave attenuation is also significantly more than that of compressional waves ($Qs = 70 << Qp = 170$) and more than originally estimated ($Qs_{original} = 300$) in this area, for the considered frequency band.

2.2 Formation micro-imager

The Formation micro-imager tool generates an azimuthally oriented resistivity image of the borehole wall (0.2" vertical resolution), using 192 electrodes spread around the outside of the tool. The resistivity image is typically unwrapped into a 2D plane for interpretation, with 3D planar features (such as fractures, faults, and bedding) represented as sinusoids in interpretation software. These planar features are fitted with sinusoids with the true dip orientation automatically generated and displayed as tadpoles. Fractures are categorised by trace conductivity-resistivity and aperture size, with a fracture density generated, and possible faults identified. Overall, 4,242 fractures were identified in the RE006 drillhole (Figure 8).

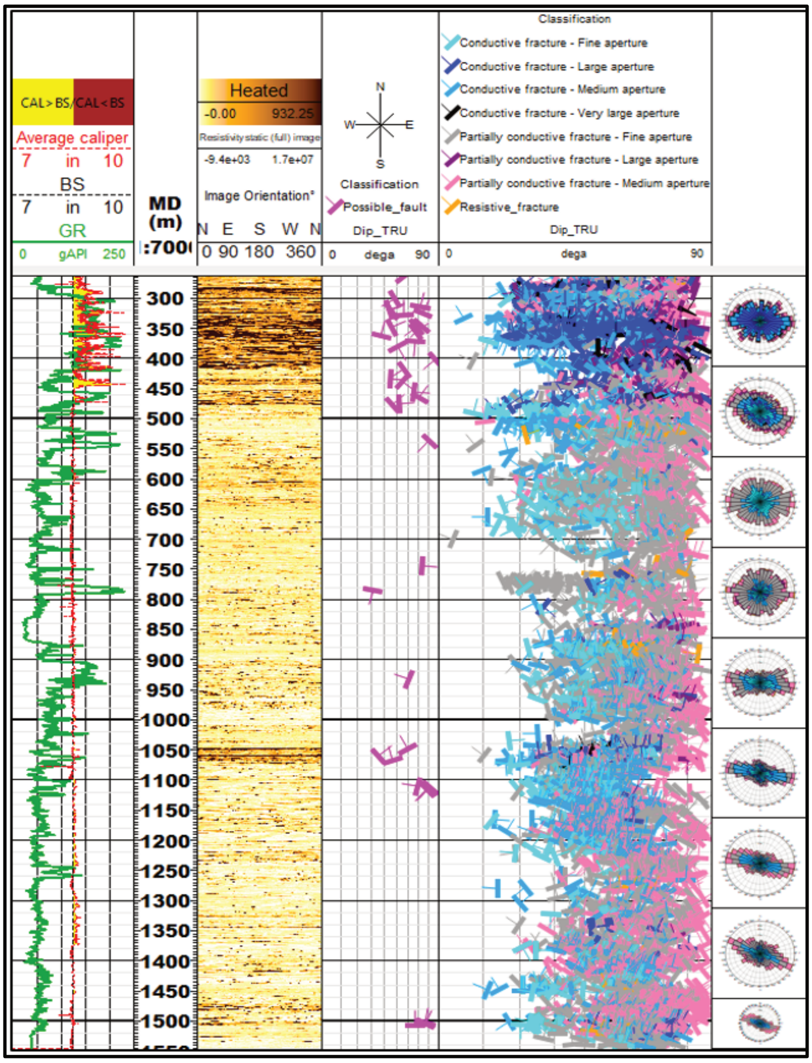

Figure 8 Formation micro-imager tool image (track 3) and interpretation outputs, displaying fault, and fracture dip-picking tadpoles, fracture strike rose plots, fracture density and zonation, and main outputs of 1D MEM (image after Lewis et al. 2021)

3 Results

Given the wealth of information, it is best to display all the available data in a single display (Figure 9), where one can see both known features as well as features not previously recognised such as vertical extension of one of the key faults (Harriet Fault – annotated with blue), and other faults above the known carbonate faults (Carb 5 – shown in red). The OVSP image competently ties with the vertical corridor stack, confirming the observed reflectivity. The interpretation of the OVSP image is aided by the interpretation of the formation micro-imager data and vice versa. The identification of faults on the micro-imager image was difficult because of the intense visible fracturing and effects of borehole wall damage on image quality but was aided by considering observed events that caused offsets in reflectivity. By examining the truncations of reflectivity in the OVSP image away from the wellbore, we can classify some events seen in the micro-imager image as faults. This analysis shows great potential in reducing the uncertainty associated with subsurface characterisation and can be used to enhance decision regarding critical infrastructure within the mine itself.

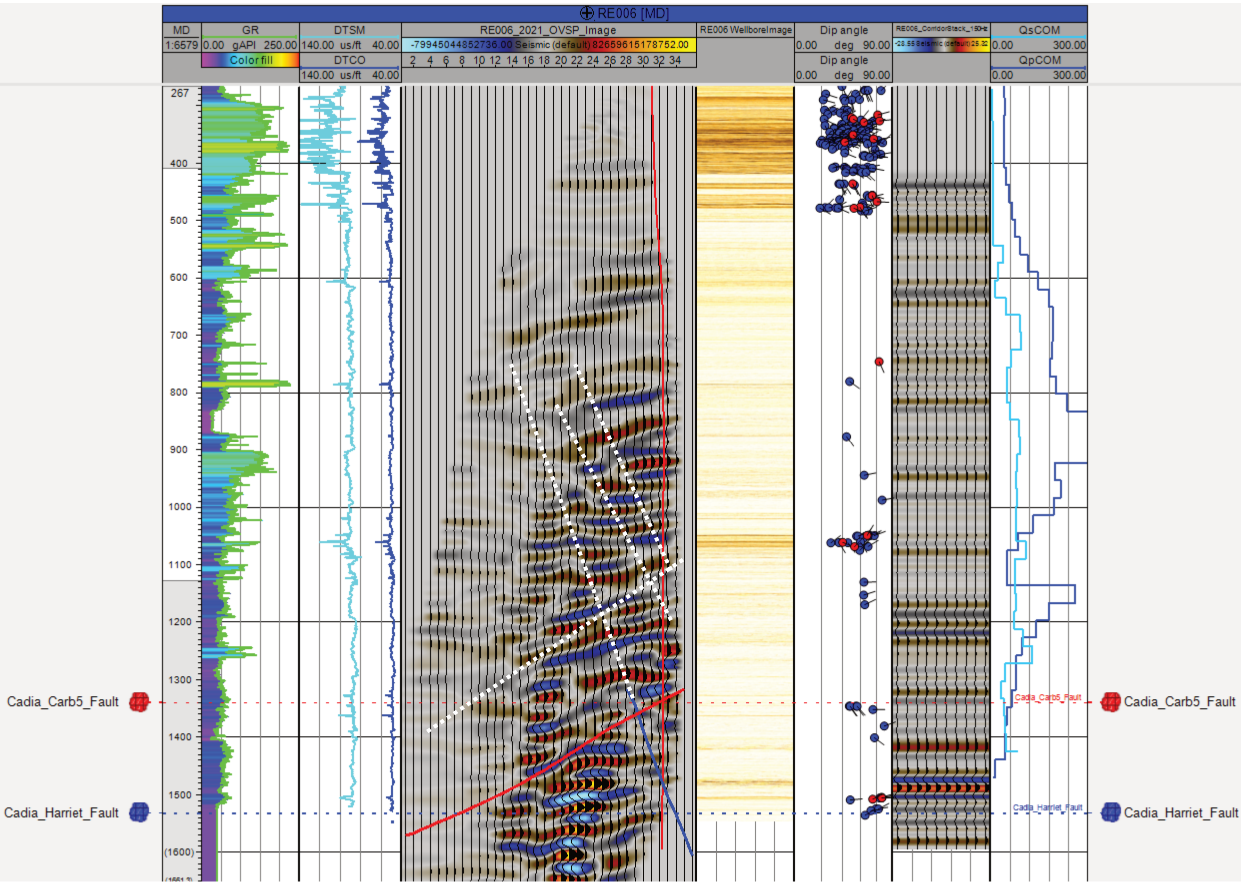

Figure 9 Integrated display of the RE006 VSPs, Wellbore Images, attenuation profiles and logs. The OVSP image (middle panel) also contain existing interpretations of the two major known faults. Additional faults have also been interpreted (white dotted lines)

4 Conclusions

We have shown how a suite of petroleum-style drillhole logs can be used to characterise the rock formations in the vicinity of a mine. This information can be collected during the appraisal drilling phase and used to design the mine with reduced uncertainty. The acquisition was quick, taking less than 12 hours for both surveys. This can be further reduced with use of distributed acoustic sensing (DAS) in place of conventional accelerometers. The natural extension of the OVSP experiment is to repeat it in several azimuths, thus allowing us to generate a pseudo-3D image of the prospect. This can better define positions and dips of faults and other geological structures prior to commencement of mine operations. In more complicated scenarios, the Multi-OVSP technique can be further extended to a full-fledged 3DVSP. The integration of the wellbore imaging greatly improves interpretation of the VSP image and vice versa. In addition, improved seismic velocity parameters can be extracted. This can improve seismic monitoring within the mine by providing a more detailed 2D or 3D velocity model that contains both compressional and shear attenuation parameters. If economic petroleum-style wireline drillhole logging is integrated with conventional mine logging of core more frequently, then it can produce more detailed 3D models, and it has the potential to reduce the number of costly diamond drill cores typically used on mining operations. It can also be used to image rock volumes next to the orebody, where drill cores are sparse, to identify potential hazardous geo-structures. Early results from these applications can bring improvements in mine design and geohazard assessment.

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