Deep Mining 2024 – P Andrieux & D Cumming-Potvin (eds)

doi:10.36487/ACG_repo/2465_19

Utilising distributed acoustic sensing for monitoring rock mass stress conditions in underground mining: a case study

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Abstract

Distributed fibre optic sensing (DFOS) technology is widely employed in the oil and gas industry for monitoring seismicity, strain and temperature during hydraulic fracturing of unconventional reservoirs. However, it is only in the early stages of application in the mining industry. This paper presents a case study on the application of distributed acoustic sensing (DAS) technology to monitor rock mass stress conditions in an underground mine.

The objective of this pilot project was to assess the viability of, and challenges associated with, installing fibre optics and their effectiveness in monitoring rock mass response to mining activities. An engineered fibre optic cable was deployed and grouted in a 200 m-deep borehole to monitor seismicity and strain. The raw DAS strain rate data were divided into two frequency bands: a high-frequency band (above 10 Hz) for microseismic processing and a 1–10 Hz frequency band for strain processing.

Microseismic events and blasts detected by the fibre were co-located with existing geophones and accelerometers to enhance event location accuracy and precision. While the existing network of geophones provided accurate event locations, the addition of DAS increased the precision of these measurements. In addition to microseismic monitoring, the energy attribute within the 1–10 Hz band of DAS strain rate data was analysed. This analysis revealed a clear correlation between elevated energy levels on the fibre during raisebore operations and a levelling off after the completion of raiseboring. The observed intermittent high and low energy levels on the fibre could be used for safety assessments during raisebore operations as these energy fluctuations reflect the impact of raisebore activities on rock mass stress.

Based on this limited dataset, DAS technology has the potential to offer valuable insights into rock mass behaviour in underground mining environments by monitoring stress and strain conditions during operations such as raiseboring, development and production blasts. When combined with existing seismic systems, DAS provides an additional data point for enhancing hazard mitigation strategies in underground mining operations.

Keywords: *fibre optics, distributed acoustic sensing, seismicity, rock mass creep monitoring, mining, geophones, data integration, raisebore*

1 Introduction

Conventional seismicity monitoring in deep mining operations has long relied on geophones and accelerometers. These sensors have been pivotal in providing crucial insights into the dynamic behaviour of

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rock masses, offering invaluable data on seismic events, ground vibrations and rock deformation. Their robustness, versatility and widespread adoption underscore their indispensable role in ensuring the safety and efficiency of mining operations. Geophones, with their sensitivity to ground vibrations, excel in detecting and characterising seismic events, ranging from microseismic activity to larger-scale events. Meanwhile, accelerometers provide precise measurements of ground motion and acceleration, providing valuable information on the propagation of seismic waves and the dynamic response of rock masses to mining-induced stresses. Together these conventional sensors form the cornerstone of seismic monitoring practices in deep mining environments, enabling ground control engineers and geoscientists to assess rock mass stability, identify potential hazards and implement timely risk mitigation measures.

Despite their proven utility, however, geophones and accelerometers are not without limitations. Their reliance on point-based measurements constrains their ability to capture the full spectrum of rock mass behaviour, particularly in environments characterised by heterogeneous geology and complex stress distributions. Moreover, these sensors are primarily suited for detecting seismic events, leaving a significant gap in the understanding of slower, aseismic processes such as rock mass creep and strain accumulation.

Distributed fibre optic sensing (DFOS) technology such as distributed acoustic sensing (DAS), distributed temperature sensing and distributed strain sensing has seen extensive utilisation in the oil and gas industry over the past decade, particularly for monitoring hydraulic fracturing operations (Dande & Angus 2021; Moradi et al. 2020; Jin & Roy 2017). This innovative fibre optic method has revolutionised the way microseismic events and strain changes are monitored during hydraulic fracturing processes.

Despite its proven effectiveness in the oil and gas sector, DAS has not been widely adopted for mining applications. The successful application in oil and gas operations demonstrates the potential for DAS to enhance safety and efficiency in mining operations by providing real-time insights into rock mass behaviour. With ongoing advancements and increased awareness of the benefits of DAS technology, the mining industry stands to benefit greatly from integrating DAS into its monitoring practices.

1.1 Distributed acoustic sensing

Fibre optic-based DAS technology is an innovative approach that complements and enhances the capabilities of conventional seismic monitoring systems. DAS works by utilising an optical fibre as a sensing medium. A laser pulse is sent down the fibre and, as the pulse travels, it interacts with the surrounding environment. Any disturbances along the fibre, such as acoustic waves or vibrations, cause changes in the light signal that are reflected to the interrogator. By analysing these changes, DAS can detect and locate events along the entire length of the fibre, making it a powerful tool for seismic, temperature and structural health monitoring (Murro et al. 2019).

The unique capability of fibre optic monitoring detects both seismicity, using high-frequency data, and slow-strain (aseismic or static ground response) phenomena, using very low frequency (< 0.1 Hz) data with the same instrumentation (fibre and DAS interrogator). Besides analysing low- and high-frequency data, measuring the energy within a specific frequency band is also beneficial in visualising how the energy content in various frequency bands evolves over time and across different locations (Ellwood et al. 2021; Feo et al. 2020). For example, focusing the analysis on the energy data derived from the raw strain rate data within a 1–10 Hz frequency band may capture dynamic ground response such as machinery vibrations, drilling or other quasi-static deformation process that fall within the frequency range.

The distributed nature of DAS facilitates the characterisation of spatial variations in rock mass response, enabling engineers to pinpoint critical areas of deformation and prioritise targeted interventions. However, it is imperative to acknowledge the inherent limitations of DAS, including its current single component nature and the difficulty it has in detecting very small magnitude events. These limitations can impact the accuracy and precision of locating microseismic events, particularly in complex geological settings.

Innovative approaches leveraging the complementary strengths of DAS and the existing seismic networks of geophones offer a promising solution. By co-locating fibre optic data with traditional geophone data it is possible to enhance the accuracy and precision of microseismic event detection. This synergistic integration not only mitigates the limitations of DAS but also harnesses the comprehensive monitoring capabilities of both technologies, unlocking new insights into rock mass dynamics and improving the efficacy of deep mining operations.

In summary, while conventional seismic monitoring sensors have been essential for ensuring the safety of mining operations, the introduction of DAS technology offers enhanced monitoring capabilities. When integrated with existing seismic systems, DAS improves the ability to capture both seismic and aseismic phenomena, thereby contributing to the improved safety, efficiency and sustainability of deep mining practices.

This paper presenst the results from a pilot project where fibre optic cable was deployed in Glencore's Onaping Depth project in Sudbury, Canada. The goal of the pilot project was to assess the application of fibre optics to monitor seismicity induced by mining along with the rock mass response to mining. Another objective was to integrate DAS microseismic data with data from existing geophones and acclerometers.

2 Project background

Glencore Sudbury Integrated Nickel Operations is advancing the development of the Onaping Depth deposit, which is accessed via the old Craig Mine complex situated on the north range of the Sudbury Basin (Simser et al. 2022). Figure 1 provides a comprehensive depiction of the mine site (old Craig Mine complex and planned Onaping Depth). The reserves of the Onaping Depth deposit commence at a depth of 2,245 m and extend to 2,720 m below the surface. Over the duration of the project (2017 to date) a thorough delineation drilling campaign has been undertaken to comprehensively characterise the deposit (Hall et al. 2024).

This drilling campaign revealed the presence of a significant fault aligned with the footwall of the main orebody. This fault, named the Red Clay fault (shown in Figure 1), dips southward at an angle of 30–45°, with the main orebody being located above the fault. It consists of a thin layer of clay gouge, typically less than 0.5 m thick, surrounded by altered rock. The total thickness of the fault damage zone ranges from less than 1 to 10 m.

The surrounding rock primarily consists of felsic-mafic gneiss with intermittent Sudbury breccia intervals typical of Sudbury footwall lithologies. Laboratory testing indicates that the host rock gneiss has an average intact uniaxial compressive strength of 291 MPa and a Young's modulus of 56 GPa. This rock is characterised as strong and brittle, with susceptibility to strainburst events. Evidence includes fracturing/spalling of the rock after every development round, with fractured slabs of rock visible in the muck piles as well as some strainbursting in active development headings. The presence of this significant geological structure poses substantial safety concerns during the mine development process along the fault zone.

The current seismic network, comprising geophones and accelerometers, monitors mine-induced seismicity from rock mass deformations related to new fracture generation. In addition to this existing network Glencore has initiated testing of new technologies such as DAS to potentially monitor gradual stress alterations within the rock mass, offering predictive capabilities for future strainburst events. Unlike high-frequency DAS microseismic data, low frequency DAS strain serves as a near-field measurement adept at detecting slow-strain (fracture-driven interactions), as proven in the oil and gas industry (Jin & Roy 2017; Ugueto et al. 2023).

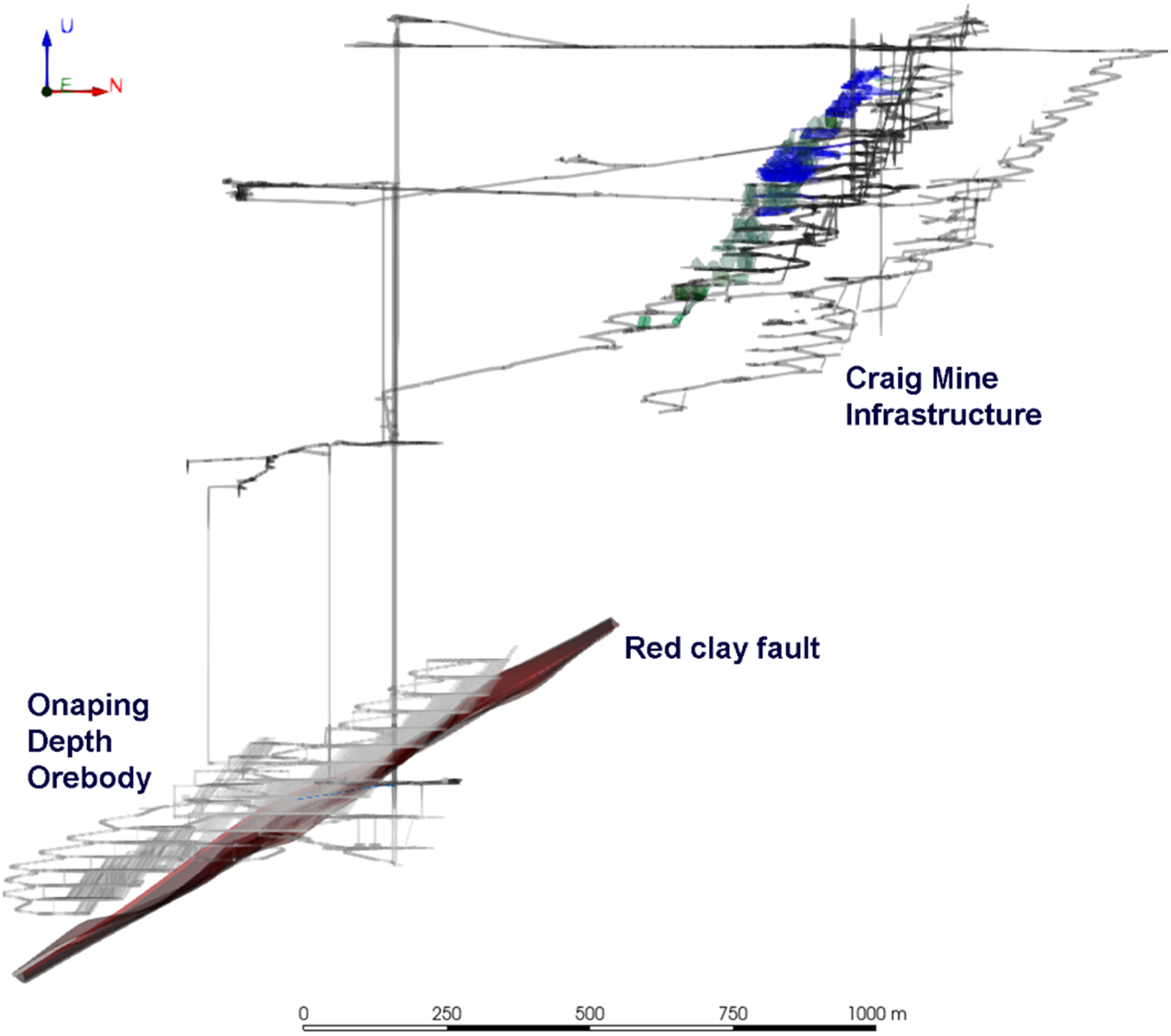

Figure 1 Glencore Craig Mine complex (existing) and Onaping Depth orebody (planned mining) along with the Red Clay fault shown in red colour. The top of the image is 1,150 m below surface and the bottom is approximately 2,800 m deep

3 Fibre optic array set-up

To monitor the mine development along the Red Clay fault, two boreholes were drilled in strategic locations: DDH 001 and DDH 002. DDH 001 (referred to as the vertical hole), approximately 100 m in length, was drilled vertically, while DDH 002 (referred to as the horizontal hole), was drilled sub-horizontally, spanning approximately 200 m and dipping at around 6°. Both boreholes have a diameter of approximately 76 mm and originate from the mine workings at the 2,490 level, with their collars situated approximately 3 m apart.

A novel approach was devised to deploy fibre optic cables in mines to optimise cost efficiency without compromising data quality. Employing a daisy chain configuration, a continuous fibre optic cable is routed from the interrogator into DDH 001 where it makes a U-turn at the bottom of the hole, traverses into DDH 002 and returns to the collar of DDH 002, where it is terminated. Given the narrow diameter of the boreholes, fibre cables had to be cut at the base of each hole, with the outer jacket removed and the downgoing and upgoing fibres directly spliced together. To safeguard these splicing points from grouting they are encapsulated within a downhole enclosure.

The trial was conducted utilising a specially designed fibre optic cable featuring one AcoustiSense engineered, and one standard, fibre string manufactured by OFS Optics. Focus was on the engineered fibre due to its heightened sensitivity. This specialised cable was exclusively grouted within the boreholes, while a single-mode fibre patch cable facilitated connectivity from the interrogator to the collar of the boreholes. The seamless integration between the patch cable and engineered fibre cable is ensured through surface splice enclosures to facilitate installation and provide the robustness required for a mining environment. The schematic depiction in Figure 2a illustrates the layout of the boreholes and the planned installation of the fibre cable as well as the surface and downhole splice enclosures.

The set-up of this daisy chain-style fibre array is not easy in underground mines because of space limitations and the fact that mining operations are ongoing. To address these challenges the entire cable assembly, including splices and enclosures, was prefabricated. Rigorous testing of the fibre splicing points using optical time domain reflectometry (OTDR) was conducted to ensure optimal light transmission without significant loss. Figure 2b shows the final assembled and spooled fibre cable ready to ship and deploy in the mine. It also shows one of the downhole fibre splice enclosures. This solution not only streamlined the installation process but also safeguarded the integrity and reliability of the cable and associated equipment.

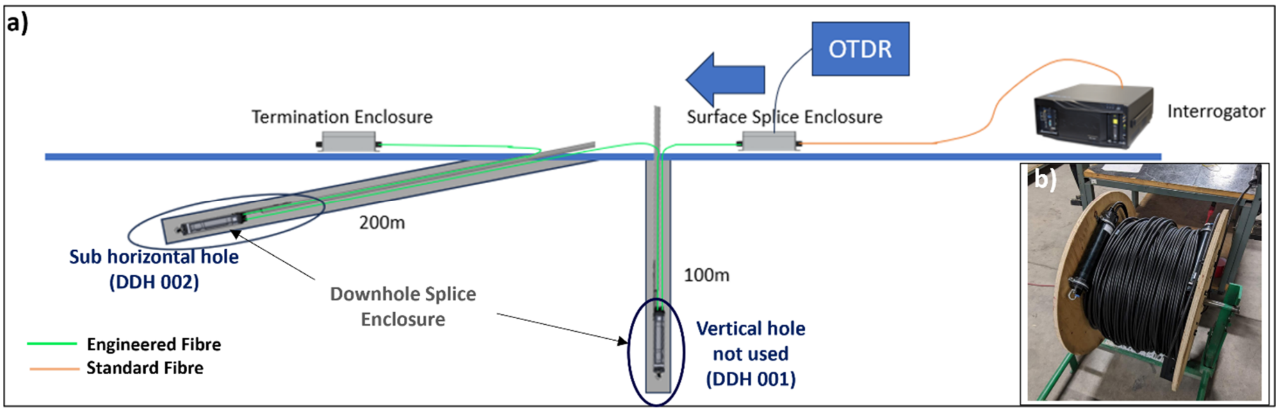

Figure 2 (a) Schematic of drilled holes and the fibre layout; (b) Assembled and spooled fibre optic cable ready to ship and deploy in the mine

4 Fibre optic array installation

The fibre was installed in holes with approximately 76 mm in diameter. To facilitate installation both vertical and horizontal boreholes were equipped with a brush and pulley system at their respective bottoms. The vertical hole allowed for relatively straightforward installation thanks to adequate clearance but the horizontal hole proved more problematic. The bottom hole splice enclosure, measuring 63.5 mm in diameter (including the enclosure lid tabs and grout tube adapter), presented challenges due to the confined space within the hole.

The occurrence of core discing during drilling of the horizontal hole indicated elevated in situ stress, which heightened the risk of hole collapse. The installation was successful despite hang-ups encountered in the horizontal hole. However, the narrow margin for error emphasises the importance of exploring alternatives to reduce the size of the splice enclosure and mitigate risks during installation. Prior to and following fibre installation, comprehensive testing using OTDR was conducted to ensure the integrity of the line. Consistent results throughout the testing process provided assurance that no breaks were present in the fibre before shotcrete was applied.

Figure 3a shows the crew installing the fibre optic cable in the horizontal hole. Figure 3b shows the collar of both vertical and horizontal holes along with the excess cable that came out of the horizontal hole, providing a visual insight into the completion of fibre installation. A decision was made to shotcrete the excess cable coiled at the collars of both holes as well as the fibre termination enclosure to prevent damage. Cable in both holes is grouted to provide the optimum coupling between the cable and the rock mass.

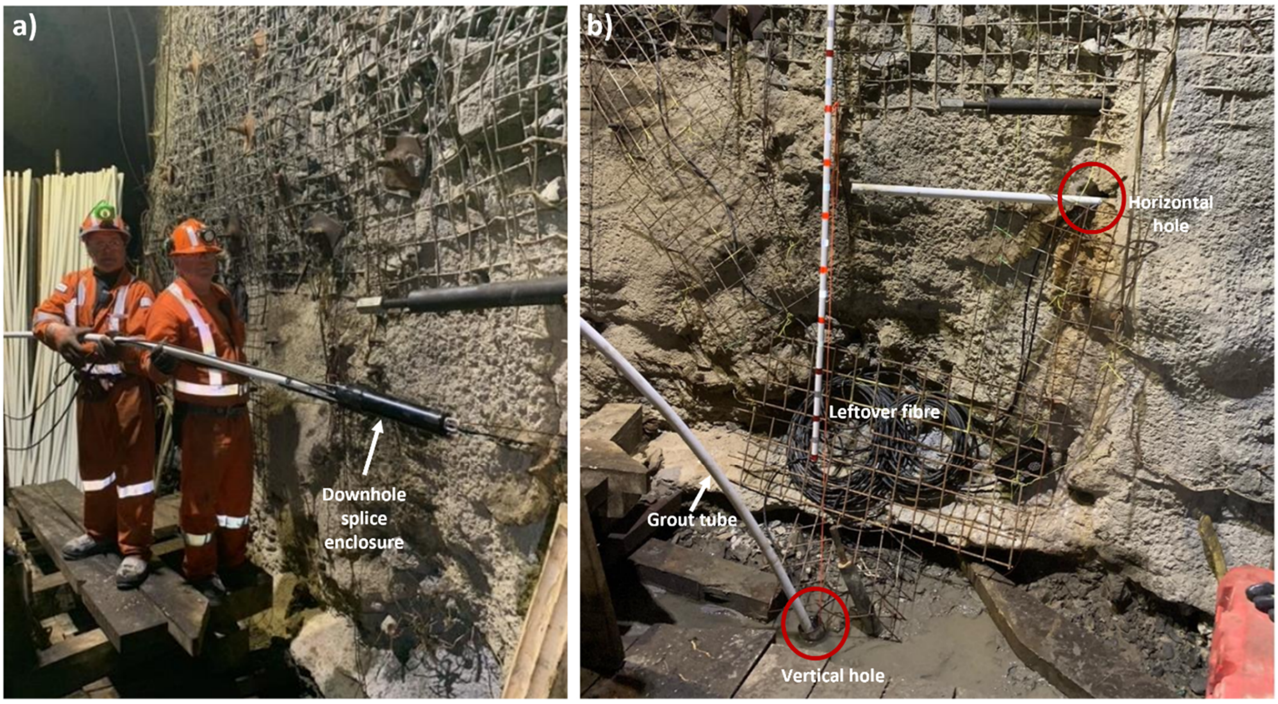

Figure 3 Fibre optic installation: (a) Crew installing the fibre into a horizontal hole (DDH 002); (b) View of vertical and horizontal hole collars after fibre installation, with leftover cable under the rebar mesh before shotcrete was applied

5 Data acquisition

With the fibre optic cable installed, the next step was to commission the DAS interrogator and associated equipment within the underground electrical substation situated approximately 100 m from the borehole collars. A single-mode fibre patch cable was utilised to connect the interrogator to the engineered fibre grouted in the boreholes. The interrogator was housed in a rack-mounted enclosure, strategically equipped with spring feet to dampen vibrations resulting from mining activities. Other essential equipment including a processing server, a data storage device and an uninterrupted power supply were housed in a separate dustproof, rack-mounted enclosure in the electric substation. The interrogator commissioning occurred after two months of fibre installation.

As this was a pilot project the equipment was initially placed on the ground. However for long-term monitoring, mounting the equipment on a wall to minimise vibrations and protect against potential water exposure on the ground is recommended to ensure sustained reliability and performance of the monitoring system.

5.1 Installation challenges

Upon commencing DAS data acquisition an obstacle was encountered in transmitting the laser light to the termination point at the end of the fibre. This issue was attributed to a break (denoted as fibre break 1 in Figure 4a) in the fibre cable between the collar of the vertical hole and the start of the engineered fibre, and was located approximately 60 m (outside of the hole) from the DDH 001 vertical hole collar. The fibre cable located outside the holes was vulnerable to accidental damage from moving equipment during mining operations.

Following repair of the cable break, a second challenge arose — the problem of transmitting the laser light beyond the collar of the vertical hole. This indicated a possible break in the cable at the point of entry into the vertical hole (denoted as fibre break 2 in Figure 4a). Removing the shotcrete to inspect for fibre breakage proved to be a daunting task.

To circumvent this challenge the decision was made to bypass the fibre buried in shotcrete and directly splice the patch cable outside the hole to one of the fibres in the horizontal hole, as illustrated in Figures 4a and 4b. This approach was designed to enable laser light transmission through both holes. After the cable was spliced, light was observed only through the upgoing and downgoing cables in the horizontal hole, suggesting the presence of a break either in the excess cable slack between the collars of the two holes (which had been shotcreted to protect the cable from damage) or in the vertical hole itself. As a result it was only possible to acquire fibre data from the horizontal hole. This incident highlights the complexities and unforeseen obstacles that can be encountered in the installation and maintenance of fibre optic systems in underground mining environments. Figure 5 shows the final horizontal hole with the fibre cable (blue colour) at the 2,490 level and the Red Clay fault.

The project faced another setback in its plan to monitor four weeks of mine development through the Red Clay fault. Following the initial week of fibre commissioning a pause occurred in mine development at the 2,490 level. This interruption posed a challenge to the project's timeline and objectives.

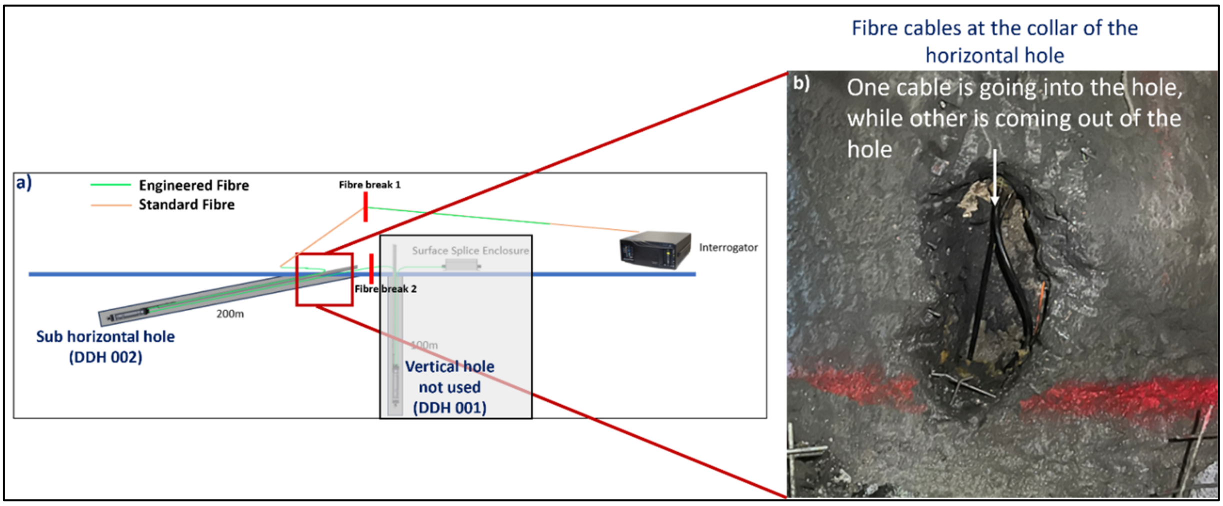

Figure 4 **Schematic of the holes and fibre layout: (a) Actual fibre layout used for acquiring distributed acoustic sensing data; (b) Exposed fibre cables at the collar of the horizontal hole, used to directly splice the patch cable from the interrogator**

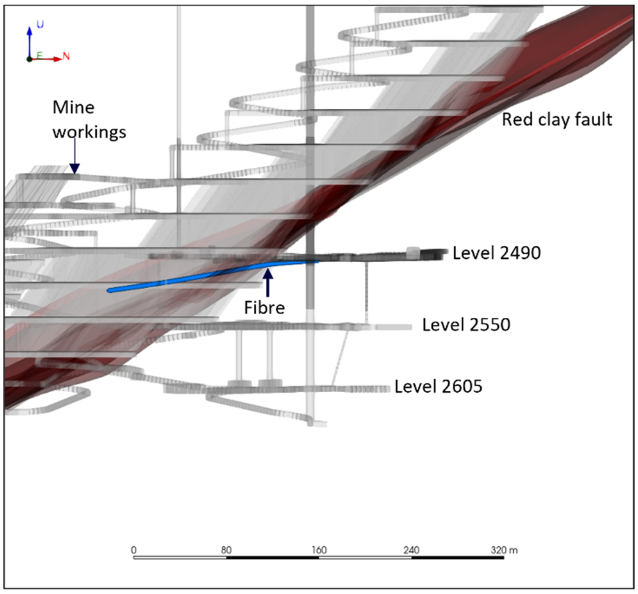

Figure 5 **Location of horizontal hole and fibre channel (blue colour) with respect to the Red Clay fault and 2490 level (level names indicate meters below surface). The fibre crosses the fault approximately 35 m from the hole collar**

5.2 Integrating with the existing seismic system

A Febus A1 interrogator was used to acquire DAS data as it has the capability to record data with precision time protocol (PTP): a network-based time synchronisation with nanosecond accuracy. Using PTP timing makes it possible to accurately time synchronise fibre data with the existing geophones and accelerometers (referred to as the seismic system) installed in the mine. This enabled co-locating of microseismic events using seismic systems and fibre. The co-location process involves finding a seismic source location using P and S arrivals from both seismic systems and fibre simultaneously. Due to technical issues, the first week of DAS was not time synchronised with the seismic system.

When acquiring DAS data, gauge length (GL) is an important parameter that defines the spatial resolution of the measurement. It refers to the length of the cable segment over which the strain rate is averaged to produce a single data point called a channel. Channel spacing is the distance between consecutive measurement points along the fibre. This project used a GL of 5 m and channel spacing of 2.4 m. This means each data point represents an average over 5 m but data points (channels) are spaced every 2.4 m, providing overlapping measurements.

A total of 230 channels were used for fibre going from the interrogator to the cable (upgoing and downgoing) in the horizontal hole. Though DAS can be acquired at a very high sampling rate of 10 kHz or more, the pilot project was limited to 200 Hz as the focus was on low frequency strain data and reducing the data volume. Even with this low sampling rate, high-quality microseismic was recorded.

Figure 6 shows an example of a large event (MW0.9) signal recorded on the fibre. The figure also displays the total fibre used for data acquisition. The top section of the image shows the fibre data outside the hole. Since downgoing fibre is at the same depths as upgoing fibre, only downgoing fibre (shown in the red dashed box in Figure 6) was used for microseismic processing.

However, in the discussion of DAS energy attribute below, the complete dataset from the fibre inside the hole is displayed to show changes in strain caused by variations in the grouting/coupling of the fibre with rock. An example of a blast signal after merging with the seismic system is shown in Figure 7. The current mine has a mix of geophones and accelerometers positioned throughout the mine. In the figure, traces are sorted by theoretical arrival times. Two single component accelerometers are located at the level of the fibre, with all other sensors installed at different levels of the mine.

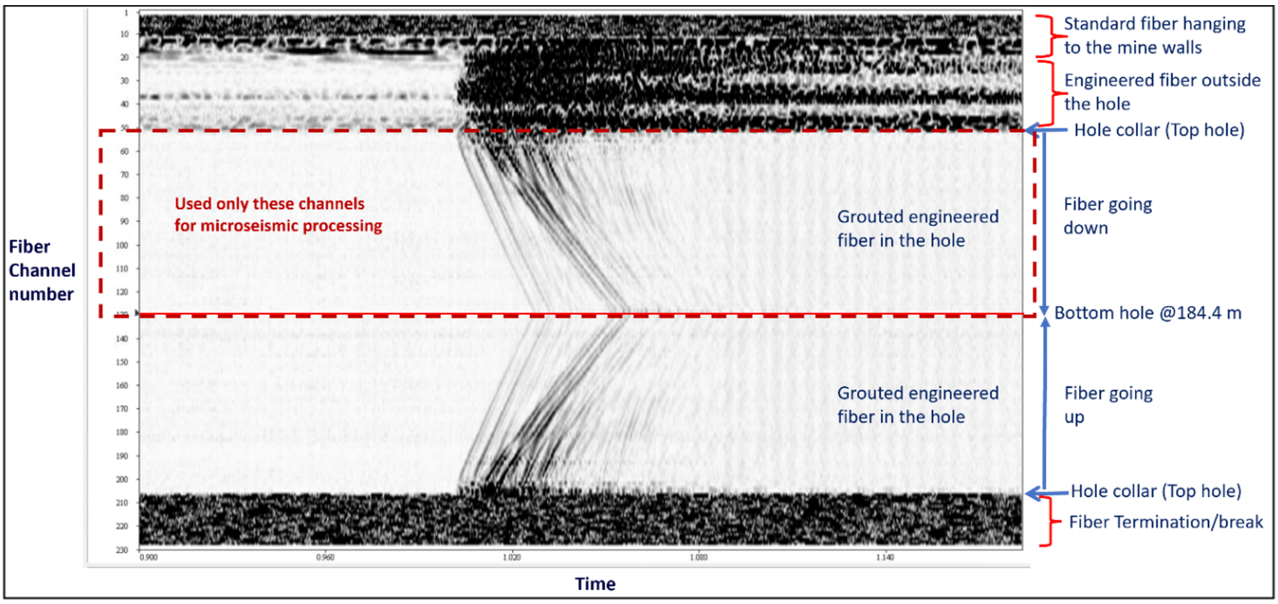

Figure 6 Example event signals recorded by fibre in DDH 002 hole. Image shows the entire fibre from interrogator to the horizontal hole bypassing the fibre in the vertical hole. The fibre channels used for microseismic processing are shown in the red dashed box

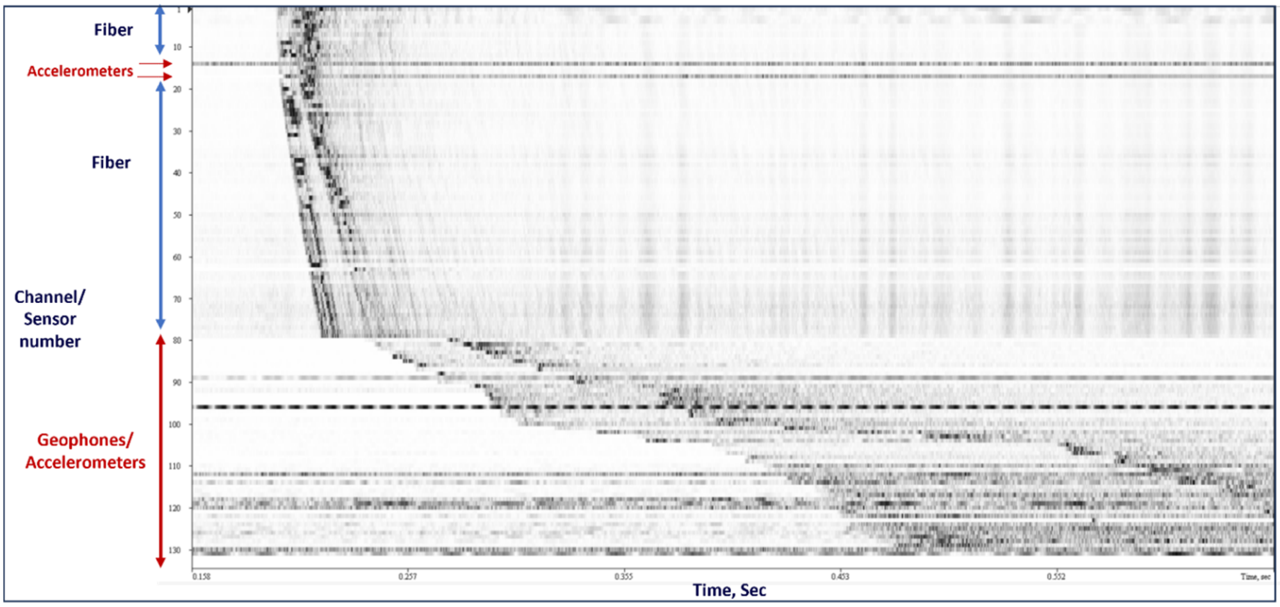

Figure 7 Example blast signals recorded on the fibre and seismic systems. Traces are sorted by theoretical arrival times. The vertical axis represents the channel/sensor number and the horizontal axis represents time. Both datasets are time synchronised using precision timing protocol

6 Data processing and results

6.1 Distributed acoustic sensing microseismic monitoring

Fibre DAS data can be used for two applications. One is for microseismic monitoring using higher-frequency data (> 10 Hz). The second involves using low frequency (< 0.1 Hz) for strain monitoring, also called slow-strain or rock mass creep monitoring. In this section the blasts and events located using the seismic system only and those combined with fibre data are compared. The next section presents the results of the energy attribute derived using 1–10 Hz band DAS data.

In DAS microseismic processing the first step is to recalibrate the existing velocity model by including the fibre data and known blast locations. This ensures an optimal velocity model for events and blasts recorded by both fibre and seismic systems. As part the calibration exercise 10 high-quality blasts that occurred during the monitoring period were selected. All 10 were located with a single isotropic velocity model using the given known blast locations. The Simplex Raytrace algorithm was an integral part of the location process. The term 'simplex' refers to the optimization technique known as the Nelder-Mead simplex algorithm. This numerical method is used to find the minimum of an objective function, which in this case measures the difference between observed and calculated travel times of seismic waves. The goal is to minimize this difference to accurately locate the microseismic event. P and S wave arrival times were automatically picked, with a manual review conducted afterward to ensure accuracy.

Figures 8 and 9 show the comparison between known and calculated blast locations using the seismic system only and the seismic system combined with fibre, respectively. Due to the high spatial resolution of the fibre data and the fact that the fibre array is concentrated along one azimuth, there is a location bias towards the fibre array. To reduce this bias every fifth fibre channel (represented as blue along the fibre array in Figure 9) was used in the location process.

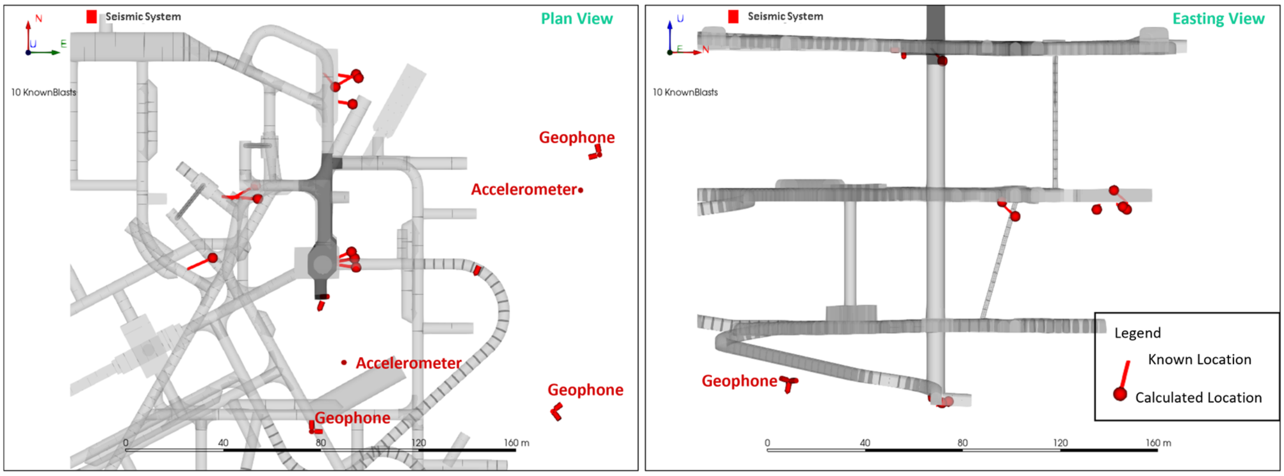

Figure 8 Known versus calculated blast locations using the seismic system. The red line shows the distance between the known blast location (northernmost end of the line) and the calculated blast location (red dot): (a) Plan view; (b) Easting view

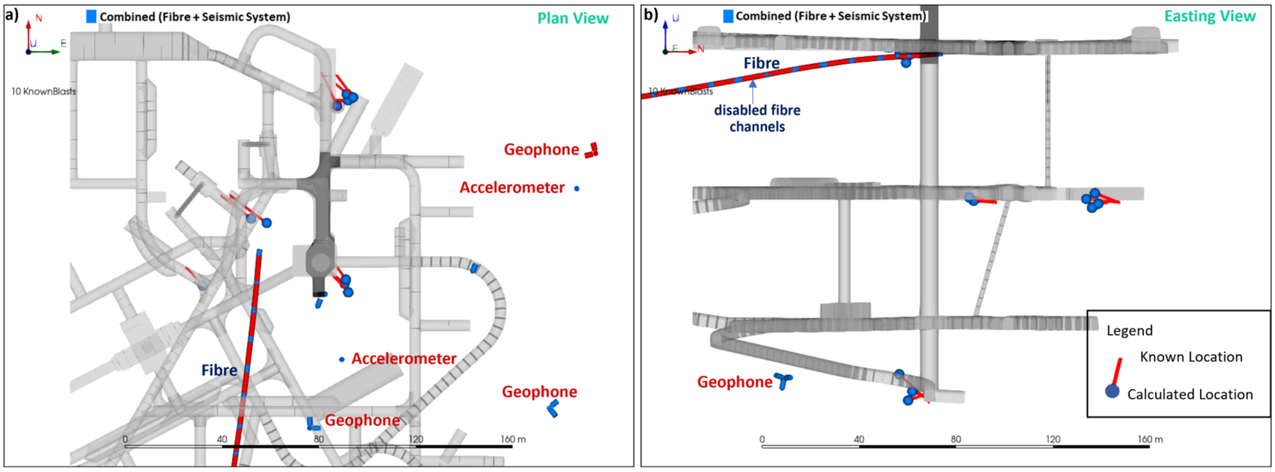

Figure 9 Known versus calculated blast locations co-located using both the seismic and fibre systems: (a) Plan view; (b) Easting view. The red line shows the distance between the known blast location and the calculated blast location (blue dot)

Table 1 presents a comparison of the Euclidean distance metrics for two methods: seismic systems alone and seismic systems combined with fibre. The Euclidean distance measures the straight-line distance between points in 3D space, incorporating differences in north (dN), east (dE) and vertical (dZ) coordinates.

The average Euclidean distance using the seismic system is 12 m, with a standard deviation of 5 m and a median of 13 m. In comparison, the combined seismic system and fibre method shows a slight improvement, with an average Euclidean distance of 11 m, a lower standard deviation of 3 m and a median of 11 m. The reduction in the standard deviation from 5 m to 3 m when combining seismic system data with fibre indicates a moderate increase in measurement precision. This suggests that integrating fibre technology with geophones can provide more consistent and reliable seismic source locations.

While there is not a significant improvement in the expected location error of the blasts due to good coverage of the seismic system, co-located blasts are better clustered with the combined method. This provides high-accuracy as well as high-precision locations. If fibre was installed in an area with a sparse seismic network, a more notable improvement in the location error may be seen.

Table 1 Comparison of Euclidean distance metrics for seismic systems only and combined with fibre

Metric	Seismic system only	Co-located (seismic system and fibre combined)
Average (m)	12	11
Standard deviation (m)	5	3
Median (m)	13	11

Figure 10 shows a comparison of events and blasts locations with and without using DAS data. Blasts are represented by stars while events are represented by dots. Locations using only the seismic system are coloured red and locations using both seismic and fibre recordings are coloured blue. As seen in the figure, the blue dots are clustered better (less scattering of the event locations) than the red dots. This is due to the addition of more data points in the form of fibre data in the event location algorithm, which improved the precision of event locations. A total of 120 seismic events occurred in the vicinity of the trial location during the approximately two-week DAS recording period when the seismic system was time synchronised with the fibre data. Only 107 of these events were recorded by the fibre. The seismic system detected more events from other parts of the mine that were not detected by the fibre, due to the high sensitivity of the accelerometers and their extensive coverage across the mine. Figure 11 shows the distribution of moment magnitude over time and compares the minimum detectability limits of the seismic and fibre systems. The minimum magnitude event detected on the fibre is MW−1.4 and MW−2.4 on the seismic system. Black and blue dots represent events detected by the seismic system and the fibre, respectively. Events detected by the fibre from 5–13 December are not time synchronised with the seismic system and may not represent accurate magnitude values due to uncertainty in event locations, attributed to the single component nature of the fibre.

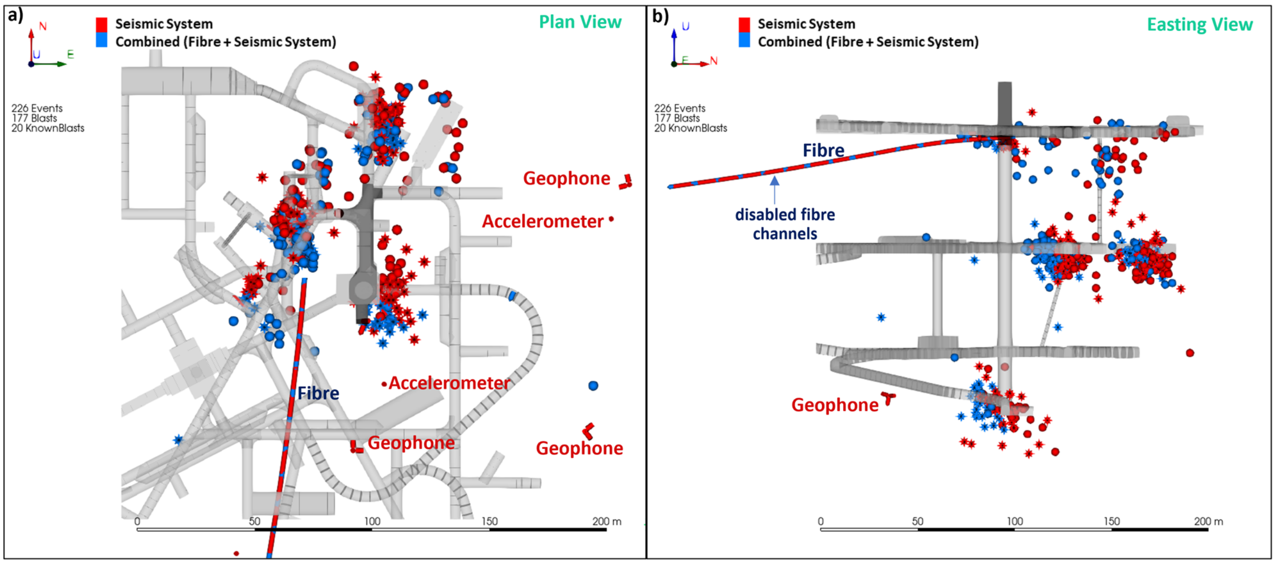

Figure 10 Comparing events and blast locations with and without using distributed acoustic sensing data. Stars represent blasts and dots represent events. Locations using the seismic system only are coloured red, while combined locations are coloured blue. The fibre array is shown as red and blue bands, where blue represents every fifth sensor used in the event location process and red represents disabled fibre channels: (a) Plan view; (b) Easting view

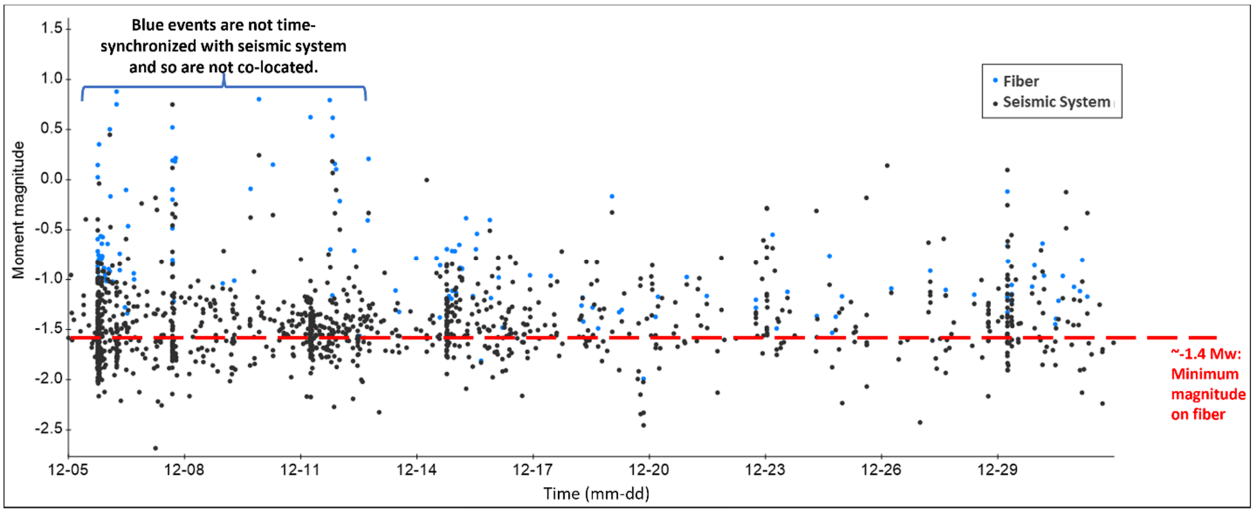

Figure 11 Distribution of moment magnitude with time for all events that occurred in the mine during the monitoring period. Black dots represent events detected by the seismic system and blue dots represent events detected by the fibre

6.2 Distributed acoustic sensing energy attribute

The energy attribute is determined by summing the squared amplitudes of the strain for every 10 seconds of data for each fibre channel (Kavousi et al. 2017), denoted in units of microstrain per second squared (με/s2). Also computed was the energy sum attribute, which sums average energy values of upgoing and downgoing fibre at each time step, providing an overview of the rock mass strain on the fibre.

Figures 12 and 13 present heatmaps of DAS energy and energy sum attributes computed within the 1–10 Hz frequency band, juxtaposed with seismic events and blasts detected on the fibre (in the microseismic frequency band) for the time periods spanning 5–20 December and 21–31 December, respectively. Events and blasts are colour-coded based on magnitude. In the heatmap, red colour represents higher energy levels, suggesting significant strain on the fibre. This strain can result in either fibre expansion or compression, depending on various factors. Typically, fibre extension is caused by thermal expansion of the cable with rising temperatures or external forces such as geological movements, structural loads or fracture opening. Conversely, fibre compression often arises from thermal contraction with decreasing temperatures or pressure from surrounding rock, such as fracture closure or convergence.

Three distinct phases of fibre response can be identified in the energy heatmaps. The first phase, occurring from 5–13 December 2023, is characterised by distinct intermittent high and low energy bands. This suggests significant activity and varying energy responses along the fibre, likely corresponding to dynamic changes and events within this period. The second phase, spanning from 13–15 December, marks a transition period. During this phase, energy bands become weaker and less distinct, indicating a reduction in activity and a shift towards more stable conditions. The third phase, from 15–31 December, is identified as the fibre relaxation period. During this time frame the energy heatmaps show minimal activity, reflecting a period of reduced stress and stabilisation of the rock mass.

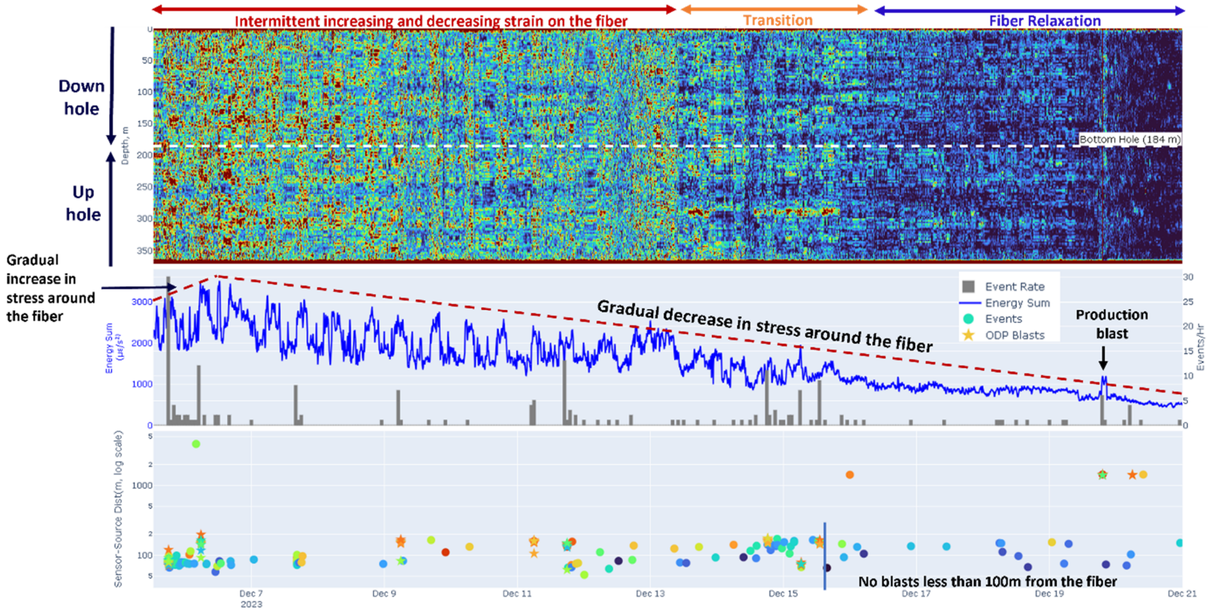

Figure 12 Heatmap of the distributed acoustic sensing energy attribute (5–20 December) using 1–10 Hz strain data (top), the distributed acoustic sensing energy sum attribute (average of downhole and uphole fibre) and event rate/hour (middle), and source-sensor distance versus time of events and blasts coloured by magnitude (bottom)

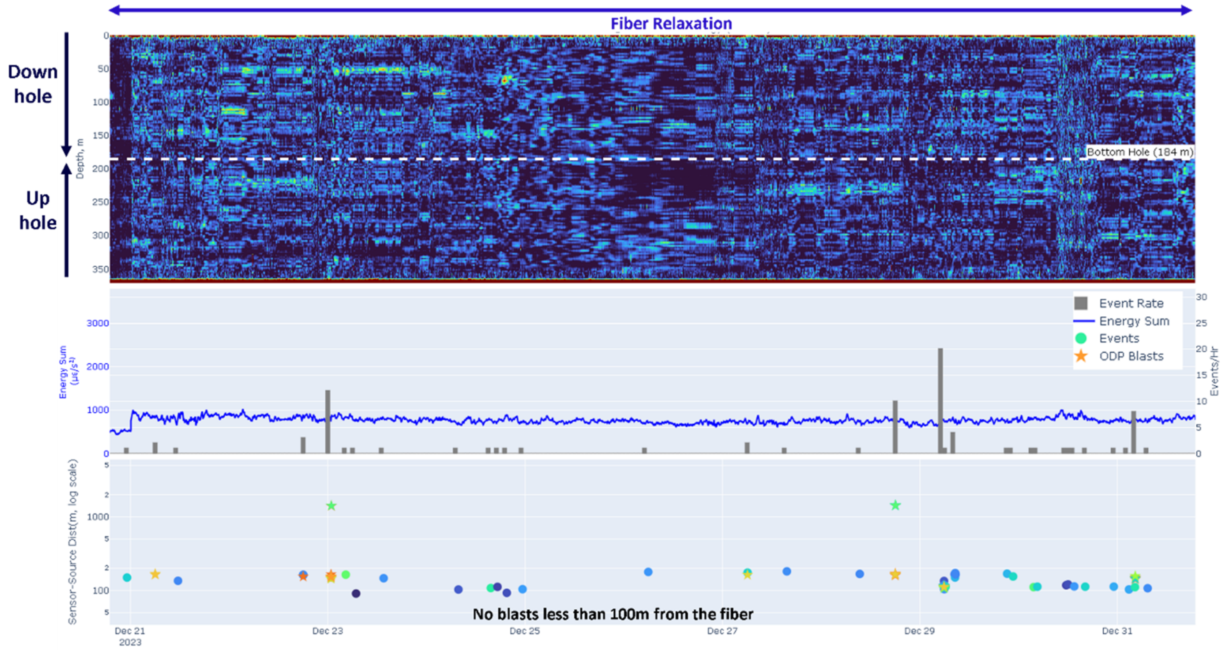

Figure 13 A continuation of Figure 12. Heatmap of the distributed acoustic sensing energy attribute (21–31 December) using 1–10 Hz strain data (top), distributed acoustic sensing energy sum attribute (average of downhole and uphole fibre) and event rate/hour (middle), and source-sensor distance versus time of events and blasts coloured by magnitude (bottom)

One of the primary factors that might have contributed to the heightened strain recorded by the fibre from 5–15 December is likely the operation of the raisebore (2.4 m diameter, 56 m length, 43 m from the top of the fibre and 220 m from bottom of the fibre), designed for a temporary waste pass from the 2550 to 2490 level, as shown in Figure 14.

There is further evidence of increased seismicity along the raisebore, particularly from 10–15 December, indicated by the green seismic events in Figure 14a. The reaming to reach final raise diameter, initiated on 28 November, completed the first 28 m of the raise length before the DAS monitoring commenced, as depicted in Figure 15 . It can be speculated that if fibre data from 28 November had been available it may have aligned with the raisebore advance rate, with the trend expected to exhibit a steady increase until raisebore breakthrough. However a change in the trend of the energy sum data was observed on 6 December. This fluctuation could be attributed, in part, to a 0.9 moment magnitude event (160 m from the centre of the fibre) that occurred on that date. It also could have been influenced by changes in geology and rock mass stress conditions as the raisebore progressed to a length of 32 m.

For approximately the first 24 hours of data acquisition (5–6 December) a progressive increase in strain on the fibre was recorded, which peaked on 6 December before gradually decreasing at midnight on 20 December (Figure 15). The initial increase in energy could have resulted from the increased rock mass stress caused by two slashes blasted (20 m from the fibre) just before the fibre recording started. From 21 December onwards the strain on the fibre remained relatively stable.

Notably, the DAS energy sum demonstrates a correlation with the raisebore advance rate from 11–13 December, as evidenced by the horizontal dotted box in Figure 15. During this interval the raisebore's advancement rate was relatively slow due to reaming within the influence of the Red Clay fault and excavation-induced stress in 2490 level. This resulted in a temporary increase in strain on the fibre before it declined when the raisbore reached the destressed fractured or yielded zone that exists around the 2490 level tunnel excavation during 'breakthrough' into the tunnel.

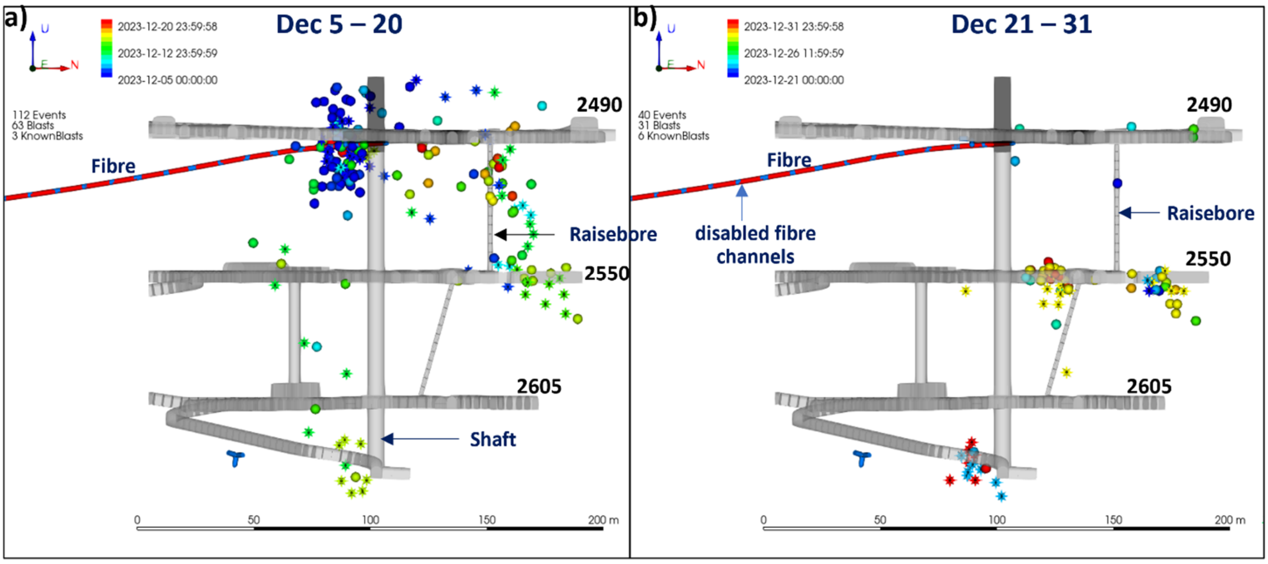

Figure 14 Easting view of events and blasts locations with respect to fibre and different mining levels: (a) 5–20 December (raisebore operation ended on 15 December); (b) 21–31 December. Events and blasts are coloured by time. The 'KnownBlasts' label in the figure legend represents blasts used for velocity calibration

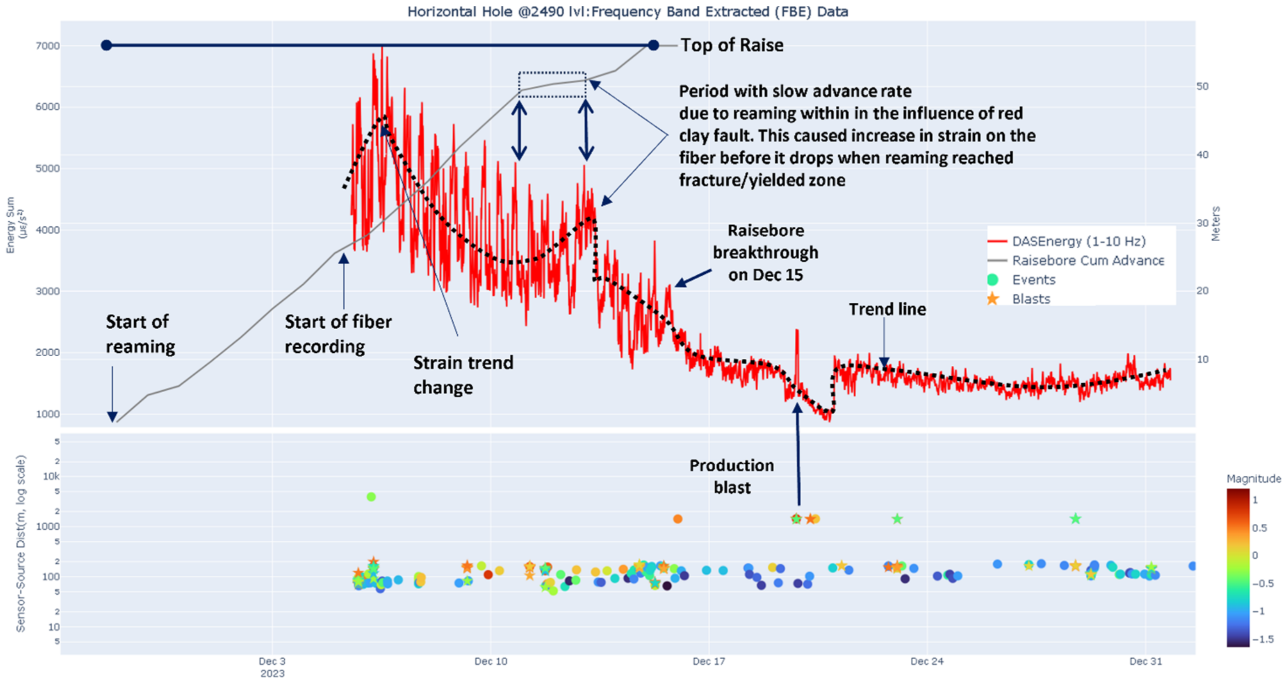

Figure 15 Distributed acoustic sensing energy sum for the 1–10 HZ frequency band overlayed by the raisebore cumulative advance rate (top), with blasts and events coloured by magnitude (bottom). Black dotted line shows average trend of the distributed acoustic sensing energy sum data

7 Conclusion and recommendations

This paper presents findings from a pilot project deploying fibre optic cables integrated with an existing seismic sensor network in a deep mine to evaluate the fibre optics technology to monitor the rock mass response to mining. The study reveals that DAS microseismic data can complement a seismic network to enhance the accuracy and precision in identifying microseismic event and blast locations.

A significant application of fibre optics is in monitoring rock mass response to mining operations, particularly through the low frequency (1–10 Hz) strain-derived energy attribute. This project suggests that there is a correlation between raisebore activity and the DAS energy attribute. The intermittent fluctuations in fibre energy levels observed are indicative of the impact of raisebore operations on the rock mass stress dynamics.

While this pilot project progressed successfully for the most part, from installation through to data acquisition and processing, several challenges were encountered along the way. One notable difficulty arose from a fibre cable break, rendering the cable in the vertical hole unusable. The decision to proceed without rectifying this issue was made because accessing the fibre in the vertical hole would have required excavating the shotcrete that had been used to protect the excess cable.

To address these challenges in the future and optimise fibre sensor utilisation in mining operations, several recommendations are proposed. Firstly, drilling long holes and installing the fibre in a daisy chain fashion could reduce the operational costs of the DAS interrogator as only one interrogator would be required to monitor multiple holes. In addition, designing holes to cover existing and future mine development and production areas would enable prolonged use of the fibre sensors over several years. or possibly over the life span of the mine. Finally, investing in a long-term rental of the DAS interrogator could mitigate overall project costs.

Fibre optics have already been widely used in various industries as monitoring tools for seismicity, strain and temperature. The mining industry can now embrace this technology to achieve precise, real-time monitoring of rock mass responses; enhancing safety, operational efficiency and risk management. Integrating DAS with existing seismic networks will enable a deeper understanding of rock dynamics, leading to safer and more sustainable mining practices.

Acknowledgement

The authors extend their gratitude to the Glencore Sudbury Integrated Nickel Operations management team for allowing installation of the fibre and for their support throughout the pilot project. The authors also acknowledge the support of Glencore and ESG Solutions management in their permission to publish this paper.

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