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Distributed fibre optic sensing for ground monitoring in underground hard rock mining

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Abstract

Managing an underground hard rock mine is an intricate engineering feat, requiring comprehensive oversight. A critical aspect of this management is ground control, focusing on addressing rock instabilities that arise from the mining processes and ore removal. Understanding the geotechnical characteristics of the rock mass and the impacts of mining operations is crucial, yet the capacity to influence ground conditions significantly differs based on the accessibility and the amount of rock at risk of instability. Despite meticulous planning and design, underground mines must be prepared for unforeseen challenges, requiring the deployment of monitoring tools to confirm the stability of specific mine sections.

Incorporating cutting-edge distributed fibre optic sensing technology into geotechnical engineering practices offers a way to enhance safety and evaluate ground conditions more effectively. This technology allows for continuous, real-time or near-real-time monitoring along a fibre optic cable; capable of detecting changes in strain, vibration and temperature through alterations in light's intensity, phase, polarisation, wavelength, or travel time within the fibre. Unlike traditional in situ mine monitoring sensors, which are limited by their discrete nature, fibre optic sensing leverages the optical fibre itself, providing a compelling alternative for these applications.

An innovative and novel application of this technology was demonstrated by Mining3/CSIRO at an underground hard rock mine located in South Australia, where a distributed fibre optic sensing installation captured detailed strain and temperature measurements in a 500 m deep installation. The system employed durable and cost-effective fibre optic cables within standard HQ diamond drill holes and connected to surface interrogators. The gathered data was processed offsite and integrated into the mine's operational systems for analysis and informed decision-making.

This paper presents continuous fibre optic monitoring as an economical, dependable approach that offers critical data to mine managers. It outlines the foundational principles of fibre optic sensing and practical installation considerations for such a system. Distributed fibre optic systems are capable of being installed in deep holes and run over extended distances, in tunnels or on the surface. They provide a comprehensive multi-parameter sensing capability beyond the reach of traditional monitoring tools. Additionally, this paper highlights the potential of fibre optic-based geotechnical monitoring technologies to significantly enhance mine safety and efficiency when integrated into the planning, design, and operational stages of hard rock mines.

Keywords: *fibre optic sensing, ground control, underground, hard rock mining, distributed sensing, strain sensing*

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1 Introduction

Cave mining requires team collaboration over multiple disciplines to operate a mine effectively and safely. The potentially hazardous nature of the work requires sound geotechnical engineering practices to ensure appropriate measures are taken when managing the mine. Of particular importance is ground control. According to the Department of Industry and Resources, Western Australia (1997), ground control can be considered as a composition of three components:

1. mine planning and design
2. ground conditions
3. ground support and reinforcement.

A component of ground conditions is the rock stress and geological structure surrounding an excavation, and the rock stress field can be further decomposed into two contributing factors:

1. pre-mining stress field
2. disturbance effects due to excavation.

The complexity of geotechnical engineering demands specialised monitoring equipment to measure geological changes. Seismic activity alters rock stress conditions, often near workforce activity centres. Effective mine management requires utilising appropriate monitoring data, both seismic and otherwise, and applying best practices. Including mine instrumentation plans during the planning and design stages allows for the monitoring of geohazards and ground conditions during initiation and production phases.

Current ground monitoring techniques provide discrete points that offer limited (low spatial resolution) insight into stress or strain variation in the ground. Distributed sensing, achievable through fibre optic sensing (FOS), involves optic fibre cables and interrogators that measure strain, temperature, and acoustic signals along the cable. Strain measurement is conducted using an interrogator located at one or both ends of the fibre.

Distributed fibre optic sensors offer significant advantages, including high sensitivity, immunity to electromagnetic interference, small size, and remote interrogation capability (Pendão & Silva 2022). These sensors provide higher spatial resolution and a better understanding of ground activity and strain profiles. This technology is already employed in structural and civil engineering to determine strain profiles in bridges, buildings, pavements, and tunnels (Deng & Cai 2007; Wu et al. 2020). This paper will explore various ground monitoring techniques currently used in mine sites.

2 Current sensing technology for ground control monitoring

Ground monitoring and control is critical in mining techniques, especially sublevel and block caving, in which the mining processes directly influence the surface and surrounding ground level. It is hence imperative to monitor various parameters that are byproducts of the mining process (i.e. underground stresses, strains, lateral deformations, and seismic response). This section will discuss traditional sensor technologies employed for ground monitoring in such underground environments.

2.1 Extensometers

Extensometers, available as rod or magnetic types, can be used to measure underground material strain (Gholinia et al. 2022). Traditionally, they measured strains at discrete points, but advancements now allow for extra-deep, multiple-point borehole extensometers. Experiments at the Jinshandian iron ore mine used such extensometers to measure strains along the borehole length (Xia et al. 2018). These measurements help validate deformations or cave growth against theoretical models of the rock mass, improving geotechnical understanding. However, the setup is costly due to multiple sensing units and is prone to operational failures when sensors are daisy-chained, as disruptions can affect downstream readings.

Field applications, like those at Jinshandian mine, integrate extensometer data with other sensors such as GPS and LiDAR to monitor surface deformation. In the Tianjan coastal region, a similar setup used long-range extensometers and piezometers to study underground aquifer deformations (Yang et al. 2019). These applications highlight the importance of underground telemetric information for improving mining efficiency and safety. However, long-range extensometers face drawbacks such as high costs, lack of continuous data, low spatial resolution, and susceptibility to technical failures. Increasing the distance between sensing units can reduce costs but at the expense of resolution, making these systems challenging to maintain and less detailed in their measurements.

2.2 Time domain reflectometry

Time domain reflectometers (TDR) are used to measure the position of the cave back in a block or panel cave that is propagating towards the surface. The length of a coaxial cable becomes shorter as it is consumed by the advancing cave back. The distance to the end of the cable is measured by injecting a known signal (e.g. a pulse) into the cable and measuring the time it takes the signal to be reflected to the injection point. The signal is reflected because of the impedance mismatch of the open or short-circuited cable at the cave back position. The propagation speed of the electrical signal in the coax cable is known to be very close to the speed of light. By measuring the round-trip time required for the signal, the distance travelled can be determined. Changes to the cable cause by kinks, moisture or breaks also affect the cable impedance and reflected waveforms, allowing cave interactions along the cable to be measured (Kane 2000).

TDR technology has been adopted from the electrical engineering field to become a valuable tool in disciplines such as monitoring soil moisture (Topp & Davis 1985) and soil deformation (Dowding et al. 2003).

Time domain reflectometry in cave back propagation has been in use since the 1980’s (Panek & Tesch 1981). Coaxial cables were installed into boreholes drilled into the walls and roofs. Early applications focused on verifying cave initiation and tracking cave growth over time using single TDR cables installed into pre-existing boreholes (O’Connor & Dowding 1984; Dawn 2019). TDR has emerged as a valuable tool for monitoring cave behaviour in block and sublevel caving mines (Benson & Bosscher 1999).

Some limitations of the technique include the influence of cable length on the reflection characteristics, including attenuations of approximately 10–15% in the reflection coefficient for every 10 m of additional cable length (Wimmer & Ouchterlony 2008). TDR is limited to providing the locations of cave movements, but not absolute movement data (Dawn et al. 2019). As with any cable deployment, TDR installations are susceptible to cable breakage following displacements in the holes, causing any potential information beyond the break point to be lost.

2.3 Networked smart markers

Networked Smart Markers (NSMs) consist of multiple instruments and a small radio transceiver, encapsulated in a rugged casing, powered by on-board batteries. NSMs utilise embedded accelerometers and magnetometers to determine small 3D orientation (tilt) changes in the device. The markers are typically installed in a daisy chain fashion and grouted in boreholes, in and around the cave. On-board radio transceivers relay the measurement data to neighbouring transceiver markers, allowing information to propagate wirelessly to the datalogger node, located on the surface (Aguirre & Lloyd 2020). The markers also record radio signal strength between markers, allowing changes caused by changes in the rock condition, rotations, or displacements of the device to be detected. The combined sensitivity of the sensors to tilt and the known installation distance between markers, enables the system to reconstruct the three-dimensional displacement of the markers relative to the initial placement. This displacement data then reflects the ground movement that the markers have experienced (Beingessner et al. 2020).

NSMs and their related Smart Marker technology , though relatively recent, have been successfully adopted at various sites, offering valuable insight to site personnel (Whiteman 2010; Brunton et al. 2016; Power & Campbell 2016). A key advantage of using NSMs is the ability to carry out monitoring without relying on fragile cable wires susceptible to breakage under severe ground movement. Traditional monitoring systems often face cable shear, especially in boreholes passing through significant fault lines high above the advancing cave. NSMs demonstrate more resilience against hole shearing and dislocations, enabling them to provide measurements of the cave back location surpassing traditional monitoring systems (Steffen et al. 2016).

One inherent limitation of this system is the spatial resolution of the measurements, which is ultimately determined by the spacing between individual markers within the borehole. Markers are spaced approximately every 2–8 m, due to the short transmission range through rock (Beingessner et al. 2020). While increasing the marker density would improve resolution there is a trade-off between the desired level of detail and the overall project budget. Another limitation is due to the daisy chain configuration and reliance on battery power. Sensors experiencing higher data activity levels will deplete their batteries faster, creating a bottleneck for data collection.

3 Distributed fibre optic sensing

Distributed Fibre Optic Sensing (DFOS) has emerged as a pivotal technology, transforming monitoring capabilities across various industries. By harnessing the unique properties of optical fibres, DFOS enables continuous and precise sensing of physical parameters along the length of the fibre. This innovative approach has found widespread applications in fields such as civil engineering, oil and gas extraction, environmental monitoring, and beyond.

DFOS harnesses phenomena such as Rayleigh, Raman, and Brillouin scattering to detect variations in temperature, strain, pressure, and acoustic signals with exceptional accuracy (Bao & Chen 2011). The concept of utilising optical fibres for sensing traces back to foundational research by Kao and Hockham in the 1960s, which laid the groundwork for subsequent advancements in distributed sensing techniques (Kao & Hockham 1966). In addition to the specific strain and temperature features mentioned in the following section, DFOS also has the potential of utilising acoustic sensing properties to measure microseismic activity and monitoring geometry.

3.1 Strain sensing

The effects of strain and temperature on the physical properties of the glass fibre can be observed by optical backscattering. During the initial trials of this project, the Rayleigh scattering properties of the bare fibre were solely used to determine the strain profile along the cable. The fibre optic interrogator employed for this stage was the optical frequency domain reflectometer (OFDR) or swept-wavelength interferometer. The complex Rayleigh scatter amplitude can be Fourier transformed to obtain the Rayleigh scatter optical spectrum and shifts in the spectral pattern can related to changes in strain or temperature (Gifford et al. 2007). The main advantage of using the OFDR is the high spatial resolution. Tens of microstrains can be achieved at reasonably high sample rates (several recordings per minute). However, the main limitation of using Rayleigh scatter for monitoring applications is that it is susceptible to both strain and temperature. Therefore, it is nearly impossible to distinguish strain changes from temperature changes, or combinations of these.

Further, when applying the method for larger lengths (> 100 m) the measurable strain range between recordings is limited as the strain range is determined by the wavelength sweep range, which is inversely proportional to the fibre length. Therefore, recordings need to be captured at high sampling rates to avoid the case where shift in the optical spectrum pattern cannot be correlated to the previous recording. While this is viable for short time monitoring solutions, it is not reliable for long-term monitoring as the individual measurement errors compound over time, plus any interruption in the recording, e.g. through a power outage, will reset the accumulated strain change measurements. This limits its usage for mining applications.

Alternatively, a strain monitoring system could be implemented using a distributed acoustic sensing system, as an alternative to the OFDR. In this implementation, the coherent scatter over a larger section of fibre (often several meters) is collected and the phase pattern is analysed rather than the spectral pattern. However, this method suffers from the same limitations previously mentioned, as it also relies on Rayleigh scatter.

3.2 Combined strain and temperature sensing

The Brillouin optical time-domain reflectometer (BOTDR) on the other hand takes advantage of the spontaneous Brillouin scattering within the fibre. The BOTDR operates by sending a pulsed light down the fibre optic cable. The backscattered light is then measured by utilising a coherent receiver, the scattering signal and a local oscillator (Bahrampour & Maasoumi 2010; Motamedi et al. 2013). The Brillouin backscattered light exhibits a frequency shift that is directly sensitive to both temperature and longitudinal strain within the fibre (Hu et al. 2021). Additionally, the Raman scattering spectrum experiences fluctuations dependent solely on temperature (Soto et al. 2011), which is measured by the same instrument. An illustration of the backscattered spectrum can be observed in Figure 1. By exploiting these phenomena, the system leverages Raman intensity variations to establish a temperature reference point. This reference is then employed to decouple the contributions of temperature and strain from the measured Brillouin frequency shift, allowing for the independent quantification of each parameter.

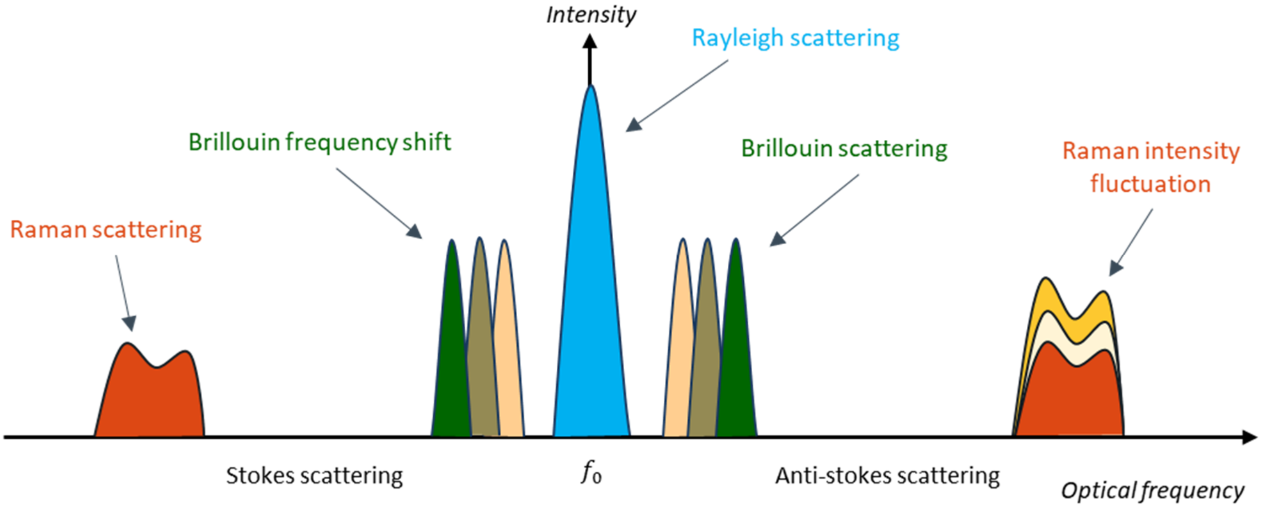

Figure 1 Illustration of the spectrum produced by Brillouin, Raman, and Rayleigh back-scattering (not to scale)

The Brillouin frequency shift has a linear relationship with applied strain and temperature fluctuations and can be written as (Equation 1) (Galíndez & López-Higuera 2012; Sun et al. 2016):

$$v_B(\varepsilon,T) = v_0(\varepsilon_0,T_0) + C_\varepsilon(\varepsilon - \varepsilon_0) + C_T(T - T_0) \tag{1}$$

where:

$v_B(\varepsilon,T)$ = Brillouin frequency shift associated with applied strain, ε, at a certain temperature, T.

$v_0(\varepsilon_0,T_0)$ = Brillouin frequency shift associated with a reference strain ε_0, at a reference temperature, T_0.

C_ε = strain coefficient.

C_T = temperature coefficient.

Calibration is a critical step for ensuring accurate BOTDR measurements. The relationship between the measured Brillouin frequency shift $v_B(\varepsilon,T)$ and the temperature and strain depend on the fibre's specific material properties, including the effective strain coefficient C_ε and the temperature coefficient C_T. These properties can exhibit slight variations depending on the fibre type and manufacturing process. Therefore, for optimal accuracy, BOTDR systems require meticulous calibration with coefficients determined for the deployed fibre optic cable.

However, due to the low power in the Brillouin spectrum, the BOTDR faces a fundamental trade-off between spatial resolution and signal strength. Due to the inherent weakness of the backscattered spontaneous Brillouin scattering, achieving high spatial resolution (less than 1 m) necessitates signal averaging over a longer time window (typically on the order of minutes). This averaging process enhances the signal:noise ratio. Further, the recordings can be referenced back to a single start or calibration recording, which significantly reduces the error accumulation in the strain change measurement.

In general, geotechnical applications only require a spatial resolution of 0.5–1 m (Dawn et al. 2019). The BOTDR sensor mechanism is particularly useful for applications where the end of the fibre is broken, left open or unreachable and hence it has the capability to provide relevant information on the ground movement to a reasonable degree. Due to the nature of the interrogator the overall time to conduct a distributed measurement along a fibre length is longer, e.g. for a 2 km cable it takes approximately 1 hour; causing this method to become a discrete form of analysis for the ground movement and 'real-time' monitoring is not feasible with commercially available of-the-shelf BOTDR interrogators.

4 Case study

Cave mining is a complex process relying on controlled cave-ins to extract the ore. Geotechnical monitoring is crucial to ensure safety and efficiency, which involves monitoring the rock mass and infrastructure to manage risk. The aim of geotechnical monitoring is to understand and confirm/disprove expectations of rock mass behaviour, assess safety/stability, and improve models. It also helps determine rock properties, scale effects, and provides data for quality control.

The field trial conducted for this case study was located at a copper-gold mine in the Gawler Craton, South Australia. The iron oxide-copper-gold deposit has a 300 m diameter and a vertical depth of 1,000 m. A sublevel caving method consisting of two 500 m lifts is employed. The ore is primarily crushed underground, and the material is delivered to the processing plant via a conveyor. There are several sedimentary layers observed in this site as depicted in Figure 2, along with an aquifer located roughly 100 m below the surface. The caving operation was designed and planned to propagate toward the surface.

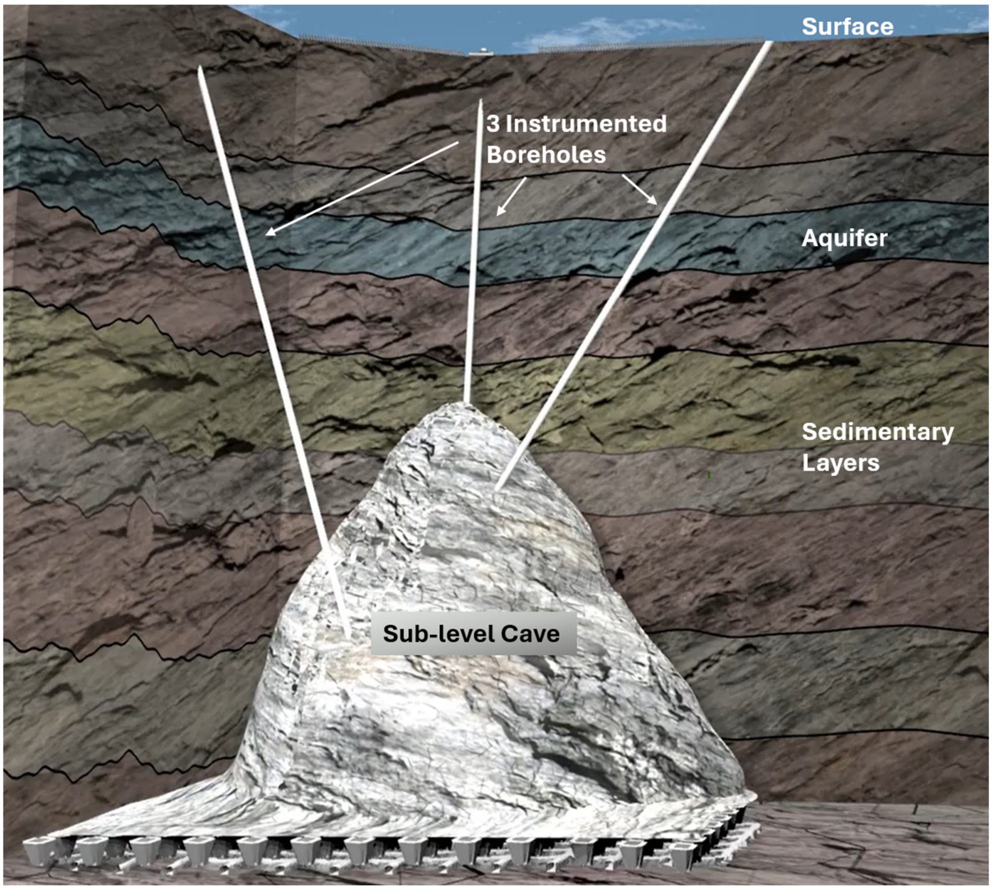

Figure 2 Illustration of the sedimentary layers, cave and instrumented boreholes extending to the cave wall (not to scale)

FOS for ground monitoring was trialled at this site. The cave was originally fitted with NSMs. As the cave breaks through to the surface, these sensors fall into the cave, breaking away from the array and hence providing information regarding cave growth.

Fibre optic sensors were installed into HQ diamond drill holes (Figure 2), alongside the NSMs to validate and expand on the information gathered from these markers. The fibre optic cable was grouted into three boreholes that extended to the top of the cave at different angles and locations. These varied angles and locations would help track cave growth in the three most probable directions. Each of these boreholes contained two individual fibre cores which could both detect underground strains and temperatures. This was done for the purposes of sensor data redundancy and hence manage and control data integrity over the course of the trial. During the trial, another fibre was installed in a ‘control’ borehole outside the caving zone, with the primary purpose to verify whether the measurements from the six monitored fibres correlated with underground strain growth due to cave propagation, rather than to random underground noise such as equipment operations or microseismic activity.

To protect the fibre optic cables at the collars, each hole was capped with a splice box housed within an environmental casing. From the splice boxes, the cables converged on a central air-conditioned container positioned outside the hazardous zones, where they were connected to a fibre optic switch and a BOTDR unit. The other end of the fibre was left exposed to the growing cave, i.e. the fibre gets consumed over time as the cave propagates. The BOTDR system provided continuous one-dimensional rock mass strain monitoring data in each hole spanning more than 300 m underground with high precision, high accuracy and low reporting latency. By employing a fibre optic switch it was possible to monitor multiple holes consecutively.

The system was programmed to take periodic strain measurements in all fibres along the course of the day, for each day of the trial. The data was regularly analysed and processed to produce distributed strain and temperature profiles along the cable. Relative strain readings were produced by comparing newly obtained strain to a datum/baseline (usually the day of installation of the BOTDR). These results were able to provide higher granularity of strain effects experienced by the fibre due to activity happening within the cave, compared to conventional sensors. The processed data was sent back to the geotechnical team for further analysis and integration into their modelling system.

The correlation between the strain in the fibre and rock strain is dependent on the coupling effects of cable and grout, rock composite, orientation and general layout. The scope of the project and field trial was limited to providing a descriptive report of the locations of strain with relative intensity as opposed to actual rock strain, which will require further modelling and designed experiments of the coupling effects.

5 Outcomes

The fibre optic cables selected for this application were military tactical grade telecommunication cables, to ensure reliable operation in harsh environments. The cables were installed at in tandem with the NSMs, with little installation overhead (reducing cost). Commissioning and terminations were completed by a standard commercial fibre optic technician. The BOTDR system was installed in the environment-controlled container with an automated data processing pipeline that required minimal maintenance.

The system captures strain over user-defined ‘virtual gauge’ lengths starting from 8 cm and measuring up to 40,000 µe (microstrain) per sensor, with a nominal precision around 20 µe. The system was set up for readings every four hours. The accuracy of the system can be improved by either increasing the measurement time or decreasing the spatial resolution. The optimal configuration depends on the specific requirements of the measurement location.

The system provided continuous monitoring over eight fibre cores covering several kilometres. The time span data from the BOTDR system used in this analysis was November 2021 to March 2023. During this time the cave was exposed to preconditioning campaigns. A single interrogator can measure multiple fibre optic cables, reducing the overall cost per hole since the fibre optic cable is much cheaper.

The relative strain plots from the instrumented bore holes provided high spatial resolution results. The data analysis indicated the presence of discrete, high-strain zones along the length of the fibre. Figure 3 shows a plot of one of the fibres extending to the crown of the cave. The relative strain measurements are increasing during the caving operation and the end of the fibre can be seen to be consumed/broken as the cave grows.

It is important to note that since the fibre optic cable is a single continuous line, any pre-mature failures or breaks will invalidate data collected beyond the break point. Hence, it is necessary to couple these readings with other inline measurements. The strain data collected from the fibre were corroborated with the NSMs data and the cave model, created from seismic surveys (Poulter et al. 2022).

This plot also depicts the spatial correlation between cave growth and regions of high strain along the fibre optic cable. Further, the heat map highlights bands of high strain, in particularly near the seismogenic zones of the cave. The observed strain bands are hypothesised to be strong indicators of impending fibre failure due to ongoing cave growth. A notable example is the increased strain activity within the bands during the mid-November to mid-December period, particularly around the 100–140 m depth range. This observation exhibits a strong correlation with the preconditioning events that were conducted around this time, which are known to induce cave growth processes.

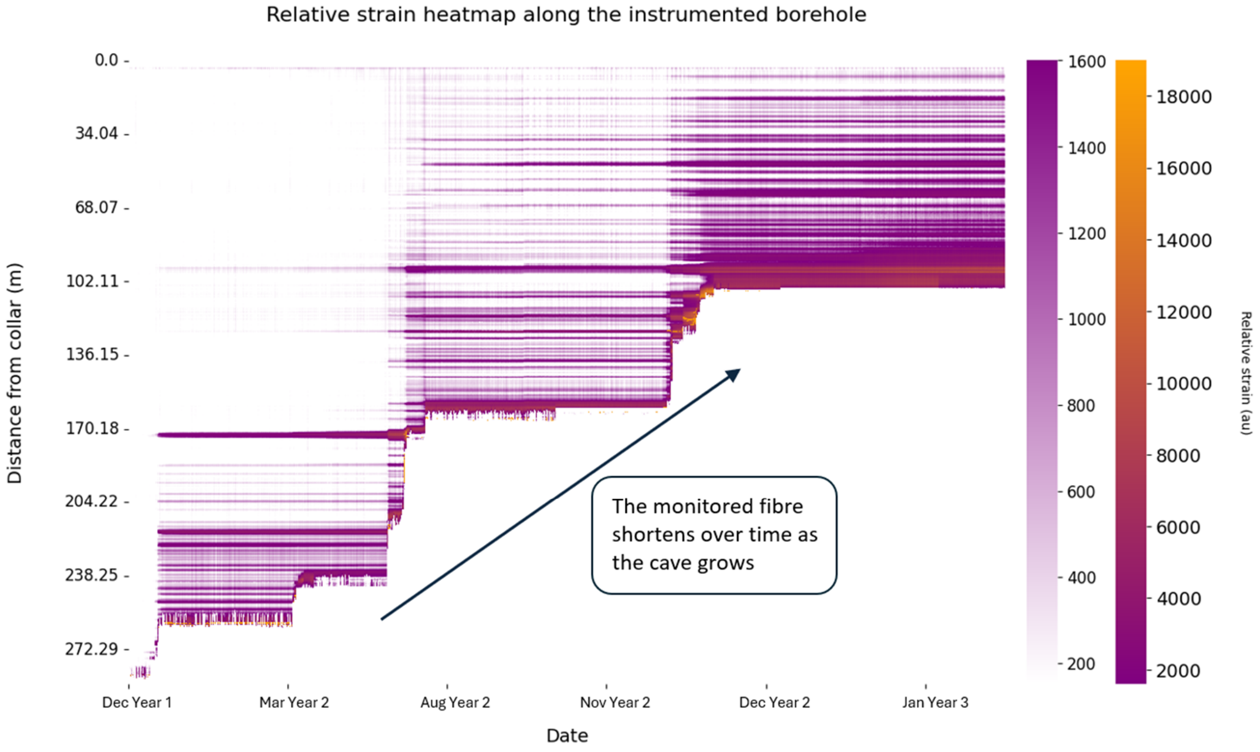

Figure 3 **Heatmap exhibiting the change in relative strain in arbitrary units (au) during monitoring period. Regions of accumulating strain and eventual breakage can be observed near the seismogenic zone above the cave back due to preconditioning campaigns**

The semi real-time data provided by the system assisted in operational decision-making processes, particularly when personnel required access near the cave hazard zone. The observed cave growth prompted an increased request for data visualisation through more frequent BOTDR logging plots. This highlights the critical role of a streamlined system capable of real-time strain measurement and reporting in informing site management strategies.

However, the system did face some limitations which included the high cost of the BOTDR unit, the need for a temperature-controlled environment for the interrogator and the higher processing time required for measurements due to averaging requirements (one to two recordings per hour). The optical fibre cable used in this trial had a maximum tensile strength of 2.2 kN. For monitoring campaigns where larger strains and/or strata separations are expected, different types of fibre optic cables should be utilised to expand the sensing range. The strain transfer from the rock to the fibre is yet to be understood and depends on the physical cable configuration. Further research is required to define the strain transfer function.

The importance of measuring strain and temperature independently is emphasised by the temperature profile shown in Figure 4. The temperature profile was recorded in the control borehole outside the caving zone. It shows a reasonably constant temperature, which matched the daytime temperature in the South Australian desert, down to a depth of approximately 80 m. The groundwater table between 80 and 90 m of depth is reflected in a significant temperature drop. However, apart from this drop, there is a consistent rising trend in temperature with a gradient of roughly 15°C over 250 m. This is a significantly steeper rise than the typical geothermal gradient of 25–30°C per km and can be attributed to the South Australian heat flow anomaly (Goldstein et al. 2009), which causes higher than usual rock temperatures. This temperature profile must be accounted for when analysing strain and/or temperature measurements near the cave.

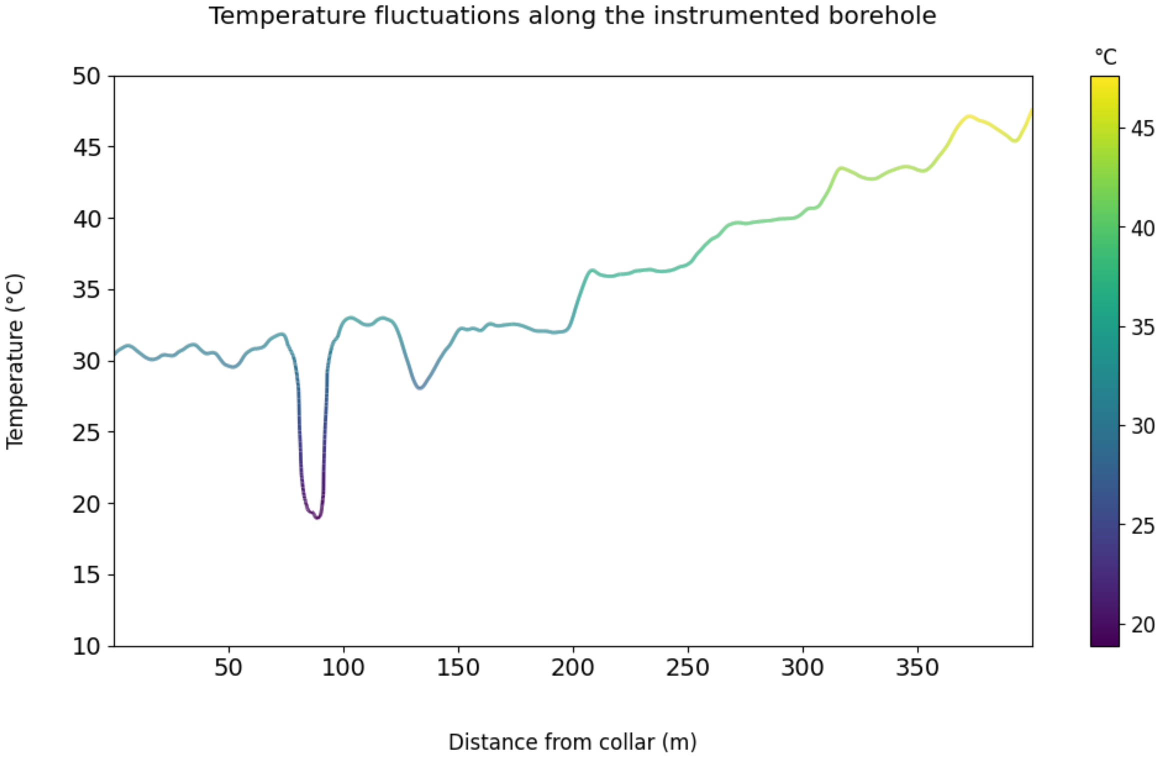

Figure 4 Temperature profile of an instrumented borehole

Overall, this fibre optic strain sensing system offers a complementary tool for various strain monitoring applications. It provides a cost-effective, easy-to-use, and reliable solution with high accuracy and scalability.

6 Conclusion

This study investigated the application of fibre optic sensing (FOS), focusing on the Brillouin optical time-domain reflectometer (BOTDR), demonstrating a successful implementation for ground monitoring in sublevel caving operations. The BOTDR system can provide continuous, high-resolution strain measurements along fibre optic cables making it a valuable tool for assessing ground stability and cave back propagation. The measurements exhibit strong correlation with data obtained from existing discrete ground monitoring instruments (NSMs). By analysing the relative strain and temperature data, geotechnical engineers were able to:

a. identify zones of deformation and strain accumulation around the cave
b. monitor the progression of the cave back and track its movement over time
c. evaluate the effectiveness of ground monitoring techniques.

The successful outcomes of these trials underscore the potential of BOTDR systems to significantly enhance safety and optimise ground monitoring techniques. As BOTDR technology undergoes continuous development and cost-effectiveness improves, BOTDRs, and DFOS technology in general, will play an increasingly important role in ensuring the safe and efficient extraction of resources in underground mines.

As mineral resources become increasingly challenging to reach at greater depths, necessitating deeper underground mining practices, novel monitoring solutions are crucial. DFOS systems offer a significant advantage in this domain, offering capabilities that may surpass conventional monitoring systems. DFOS can be deployed in significantly deeper boreholes, across extended tunnel distances, and even on the surface, enabling multi-parameter sensing and monitoring. Analogous to a network of hyper-sensitive nerves, the DFOS network acts as a distributed sensor array, continuously 'feeling' and recording the minute changes in strain and temperature that occur within the mine.

Future considerations could explore the integration of BOTDR data with other monitoring techniques to create a more comprehensive understanding of ground behaviour. Additionally, further research is needed to understand the degradation of the fibre over time, optimise data analysis methods and develop real-time warning systems based on BOTDR measurements.

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