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Field learnings and future directions of distributed fibre-optics sensing technology in cave management

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Abstract

Distributed fibre-optic sensing (DFOS) technologies are increasingly being explored in the mining sector for their potential to support improved understanding of rock mass behaviour and assess geomechanical risk. This paper shares insights from recent deployments of DFOS systems, particularly in block cave environments, where monitoring stress redistribution, fracture development, and structural activation is critical for safe and efficient operations.

Drawing on field experience and collaborative trials, we examine the geotechnical applications of both distributed acoustic sensing (DAS) and distributed strain sensing (DSS). The paper outlines strategies for system design and deployment to provide high-resolution, integrated measurements of strain and microseismicity. Depending on site infrastructure and project goals, DFOS systems can be configured for real-time monitoring and alerting, with outputs that can generate sub-metre scale 3D of cave fronts and surrounding rock mass representations depending on configuration. These observations can support hazard assessment, including seismicity and early indication of cave propagation

Recent advancements have improved sensitivity and reduced cost, making DFOS more accessible for broader adoption. Parallel progress in data analytics and visualisation tools has further enhanced the interpretability of DFOS outputs. While DFOS is still emerging in mining applications, it is increasingly evaluated as a complement to conventional monitoring approaches, and in some cases may provide additional capabilities.

Successful implementation of DFOS systems in mining environments requires collaboration with professionals who specialise in fibre-optic sensing systems and services and understand its unique characteristics in geotechnical applications. This domain-specific expertise is essential for designing, deploying, and interpreting DFOS data effectively.

We conclude by outlining current limitations and future directions for DFOS in cave mining, offering a detailed review of system design, installation, commissioning, and data analysis developed through interdisciplinary collaboration between DFOS experts, geotechnical engineers, and mine operators.

Keywords: *distributed acoustic sensing, distributed fibre-optics sensing, block cave monitoring, microseismic monitoring, geotechnical instrumentation*

1 Introduction

This paper is written for mine geotechnical engineers and integrates recent studies from other research as well as field learnings from distributed fibre-optic sensing (DFOS) deployments in mines with a focused review of recent distributed acoustic sensing (DAS)/distributed strain sensing (DSS) systems for geotechnical monitoring. After summarising DFOS sensing systems most relevant to geomechanics, we review representative applications in seismic and deformation monitoring, then describe practical considerations

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for turning DFOS systems into a mine-ready platform. We conclude with cave-specific system design guidance, limitations, and a roadmap for future DFOS-enabled cave management workflows.

2 Distributed fibre-optics technology

DFOS uses intrinsic light–matter interactions in optical fibre to measure spatially continuous changes in physical conditions, commonly dynamic strain/vibration (often termed acoustics), as well as temperature and strain, along fibre lengths that can extend from hundreds of metres to many kilometres (Lalam et al. 2019; Bao et al. 2021; Lu et al. 2019).

A DFOS system typically comprises an interrogator unit that launches short optical pulses into the fibre and records the backscattered signal as a function of time (or frequency), thereby localising measurements along the fibre (Bao et al. 2021; Russell et al. 2025).

The dominant scattering mechanisms used in DFOS are Rayleigh (elastic) backscattering, and Brillouin and Raman (inelastic) scattering. Rayleigh backscatter arises primarily from microscopic refractive-index fluctuations within the glass and is widely used for distributed measurements of dynamic strain/vibration e.g. DAS and, in some architectures, strain via spectral/phase tracking. Raman scattering is strongly temperature dependent (typically via analysis of Stokes/anti-Stokes components), making it well-suited to distributed temperature sensing with metre-scale localisation over long distances. Brillouin scattering exhibits a frequency shift that depends on both temperature and strain, enabling distributed strain–temperature monitoring with well-known trade-offs between range, spatial resolution, and acquisition time (Lalam et al. 2019; Bao et al. 2021).

Because the sensing fibre itself is passive, lightweight, and immune to electromagnetic interference, DFOS can be deployed in harsh industrial settings to obtain dense spatial coverage, effectively 'virtual sensors' every metre or less, depending on configuration (John & Hoehn 2024; Furlong & Anderson 2022).

A practical limitation has historically been turning large DFOS datasets into robust, decision-ready insight; however, advances in instrumentation and signal processing continue to improve interpretability and operational integration (Shao et al. 2025; Shi et al. 2025).

In mining geotechnical monitoring, DFOS is increasingly evaluated as a platform for capturing both microseismic/seismicity-related signals (via DAS) and distributed deformation/strain response (via DSS) in boreholes and mine headings, complementing conventional point sensors and potentially enabling a proactive rock mass response assessment when integrated with suitable processing workflows (Anderson & Parker 2024; Dande et al. 2024).

3 State-of-practice review: distributed acoustic sensing/distributed strain sensing in geotechnical and seismic monitoring

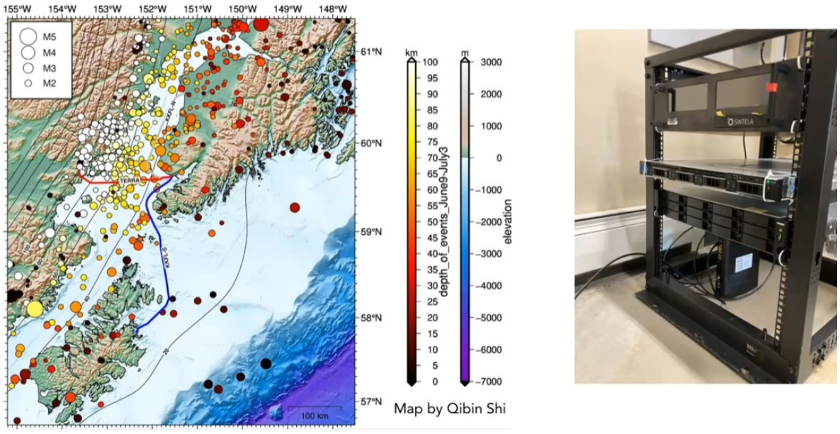
DAS and DSS systems are increasingly being adopted in the geosciences and sub-surface monitoring where the technology is used for earthquake and microseismic monitoring, mining geotechnical, longwall coal, and block cave monitoring (Fernández-Ruiz et al. 2020; John & Hoehn 2024) among other geosciences applications.

Although the examples below span geoscience and mining contexts, they are also relevant to cave mines because they demonstrate fibre layout scenarios, how DAS improves microseismic event detection and spatial coverage, and how distributed strain reveals localised deformation that precedes damage. These learnings are applicable to block cave monitoring, cave-back tracking, and hazard assessment in caving operations.

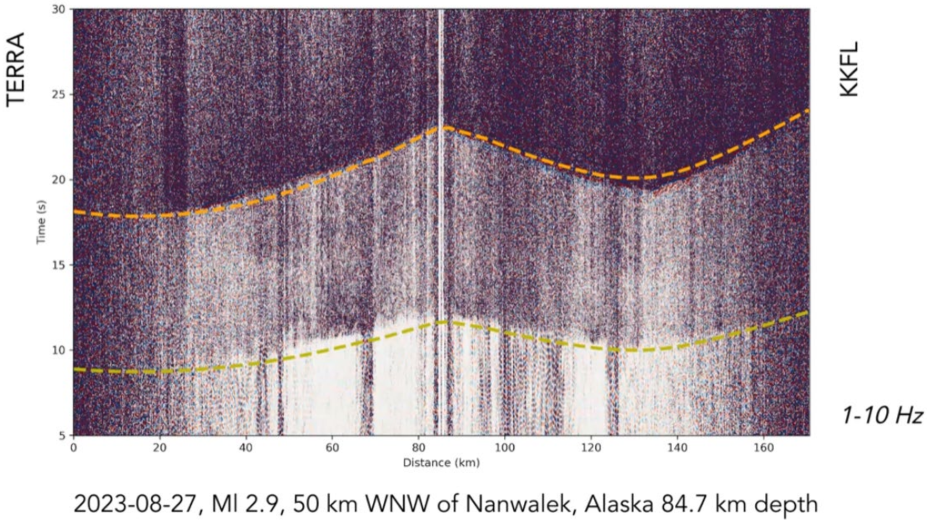
For underground applications, fibre-optic sensing cables are often installed in grouted boreholes for improved strain transfer and signal fidelity. Where practical, multiple boreholes are daisy-chained to extend the coverage. This allows for continuous observations spanning both high-frequency (seismic) and low-frequency (strain) recordings; indicators of stress redistribution and deformation.

3.1 Earthquake detection and mine microseismic monitoring

In the first example, researchers at University of Washington deployed a dual channel ONYX™ DAS interrogator on 2 offshore telecom fibre-optic cables in Cook Inlet, Alaska, and recorded detailed earthquake wavefields despite strong ocean-generated and instrumental noise (Figure 1). The results show that offshore telecom fibres interrogated with DAS can function as dense seismic arrays, enabling earthquake detection, and seismological analysis (Shi et al. 2025).



(a)



(b)

Figure 1 (a) ONYX distributed acoustic sensing (right) used to acquire data on 2 fibres shown on the map (left): the east–west cable shown in red, and the north–south cable shown in blue; (b) Dashed lines indicate P- and S-wave arrivals. Reproduced from Williams (2023)

Downhole DAS is also effective for passive seismic monitoring, particularly since recording at depth provides superior SNR, avoiding near-surface attenuation. In earthquake seismology. Lellouch & Biondi (2021) note that vertical downhole DAS arrays can detect low-magnitude events with sensitivity comparable to dense surface arrays and, in some settings, outperform regional networks. Figure 2 illustrates an earthquake recorded on a vertical downhole DAS array, showing P-wave and S-wave arrivals and the contrast between near-surface noise and deeper, higher-SNR recordings, this is the observation in underground mines of DAS applications where operational noise can mask weak rock-mass signals (Lellouch & Biondi 2021; Lellouch et al. 2021).

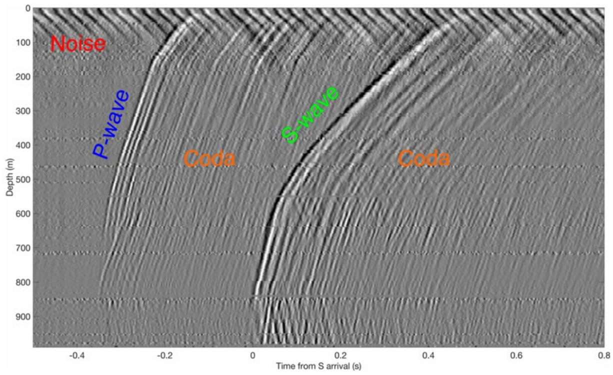
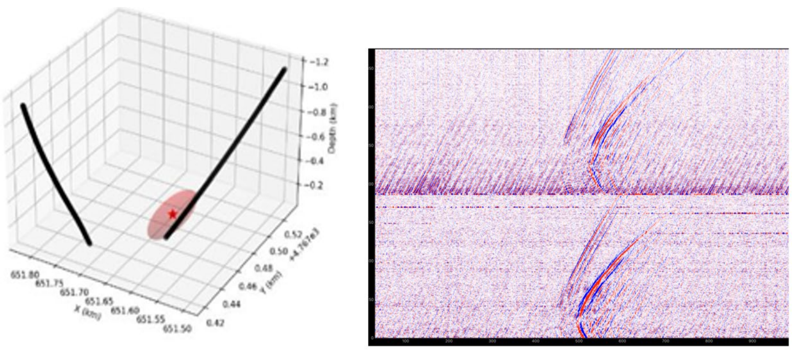


Figure 2 Distributed acoustic sensing recording of an earthquake in a vertical borehole. Reproduced from Lellouch & Biondi (2021)

Compared with conventional seismic arrays, DAS captures high-fidelity waveforms, including P-waves, S-waves, reflected phases, polarity reversals, and moment-tensor-relevant information, over multi-kilometre borehole lengths. This enables more accurate event location in heterogeneous rock mass through increased ray path coverage and reduced velocity ambiguity. DAS's ability to detect small magnitude microseismic clusters that delineate cave propagation zones, monitor evolving stress conditions in deep mines, and support high-resolution tomographic imaging has been presented in other case studies (Figure 3) (Anderson & Parker 2024).



(a) (b)

Figure 3 (a) A seismic event located by distributed acoustic sensing acquisition on 2 fibre-instrumented boreholes; (b) Example waveforms on each of the boreholes showing P and S arrivals a near borehole seismic event. Adapted from Anderson & Parker (2024)

3.2 Strain and deformation monitoring

Nowak et al. (2024) present a field-scale application of strain monitoring during a bulk pillar removal in an active underground metal mine. Where they monitored approximately 2,700 m^3 of rock mass volume. The results indicated patterns of extensional strain near removed pillars and compressional strain above remaining pillars, with the highest strain magnitudes localising around a known weak bedding contact (the '55 shale'), demonstrating the application of technology in detecting delamination, bedding separation, and stress redistribution. Figure 4 demonstrates the resolution and sensitivity of DFOS, its ability to identify hazardous deformation, and how strain evolves in response to mining-induced stress redistribution. The results in this figure illustrate the sensitivity of DFOS to mining-induced deformation, including the development of extensional zones near removed pillars and compressional loading above remaining pillars, as well as strain localisation around weak bedding contacts.

The study demonstrates that DFOS enables cost-effective, distributed strain measurements with high-spatial resolution, allowing rapid deployment over large volumes of rock. The system captured strain responses associated with pillar removal, providing insight into rock mass behaviour during excavation. Compared to conventional extensometers, such monitoring would be impractical or prohibitively expensive. The results highlight the potential of DFOS to support geomechanical interpretation and contribute to improved calibration of numerical models at the mine scale.

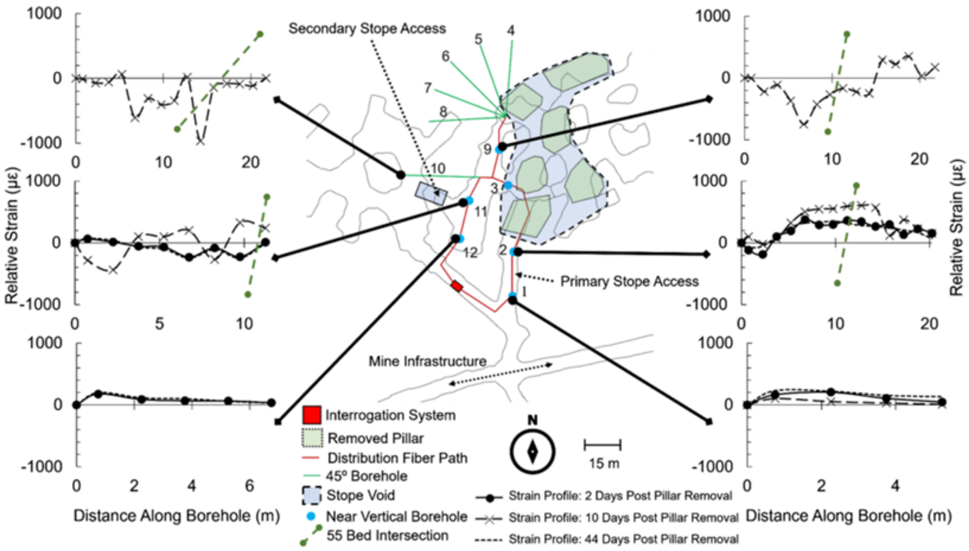


Figure 4 Strain measurements recorded at 2, 10, and 44 days after pillar removal, illustrating the evolution of tensile (positive) and compressive (negative) strain within the rock mass. Reproduced from Nowak et al. (2024)

3.3 Longwall coal monitoring

Conventional microseismic monitoring in underground coal mines is constrained by restrictions on in-mine electronics in potentially explosive atmospheres and by the practical challenges associated with deploying and maintaining dense sensor networks (Chambers et al. 2025). DAS addresses some of these limitations by enabling measurements along passive fibre-optic cables, with optoelectronic interrogators located at the surface. Field deployments in longwall mining environments have demonstrated that DAS can function as a dense, linear array capable of recording both seismic wavefields propagating through the rock mass and acoustic signals within mine workings (Chambers & Shragge 2023). These measurements exhibit clear waveform moveout and capture near-field dynamic responses associated with mining-induced events, providing insight into acoustic processes at the longwall face. Figure 5 shows waveform records obtained from fibre deployed along the longwall face demonstrating a distinct event onset, elevated background noise associated with mining equipment, and prolonged coda linked to material ejection and settling processes, illustrating the capability of DAS to capture near-field seismicity and dynamic rock mass response in active mining conditions.

More recent work has expanded on these concepts by investigating a range of deployment geometries, including installations along gateroads, boreholes, mine floors, and support structures, to evaluate the feasibility of DAS for broader seismic monitoring applications in longwall coal mines (Chambers et al. 2025). While further development is required before routine implementation, these studies indicate that DAS offers a complementary approach to conventional seismic systems by improving spatial sampling and enabling flexible monitoring configurations in challenging underground environments.

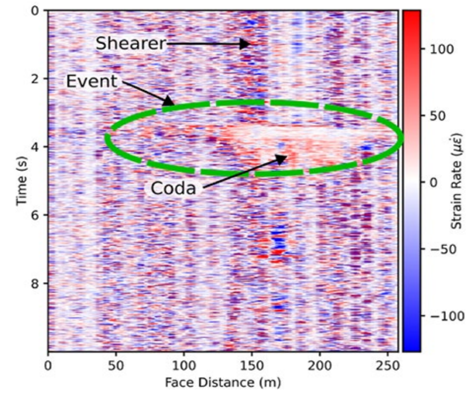


Figure 5 Example distributed acoustic sensing waveform recorded from fibre deployed in the longwall cable tray during a M 1.8 face burst. Reproduced from Chambers et al. (2025)

In another study, Liu et al. (2026) demonstrated the effectiveness of DFOS for high-resolution, continuous monitoring of mining-induced coal overburden deformation using a three-dimensional physical model. They applied pulse-prePump brillouin optical time-domain analysis (PPP-BOTDA). By integrating PPP-BOTDA technology with internal displacement sensors, the authors captured the progressive evolution of overburden failure, periodic weighting events, and caving behaviour during longwall face advance. Weighting events refer to periodic roof pressure events, moments when the overburden (roof strata) collapses, fractures, or shifts downward, causing a sharp increase in load on the working face.

Their results showed that changes in the Brillouin frequency shift (BFS) profiles correspond directly to the intensity of strata movement, enabling early detection of micro-deformation and fracture propagation prior to visible failure. Notably, DFOS identified 16 periodic weighting events with strong agreement across optical and displacement datasets, and measured failure heights 7–15% higher than surface observations, highlighting its sensitivity to subtle internal damage. Figure 6 illustrates the full sequence of overburden collapse and compaction by showing the evolving Brillouin shift curves along 3 vertically embedded fibres throughout the mining process, providing a complete distributed record of rock mass response (Liu et al. 2026). The figure shows the stepwise evolution of the BFS curves reflects periodic roof pressure events and increasing deformation intensity, with compressed zones at the fibre bases indicating the formation of the caving zone.

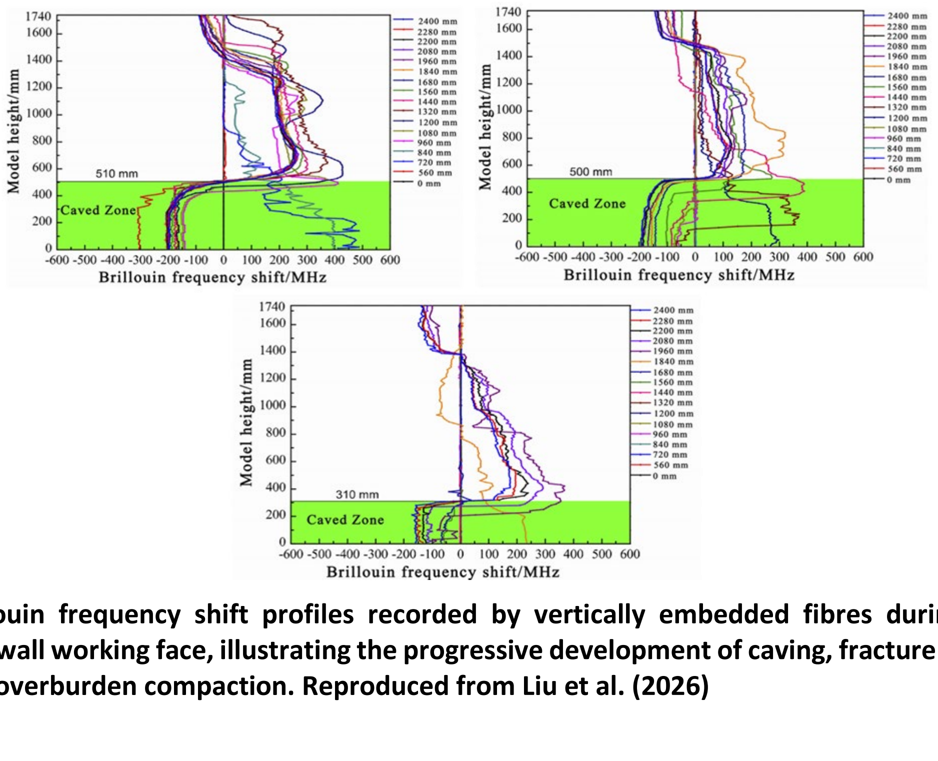


Figure 6 Brillouin frequency shift profiles recorded by vertically embedded fibres during simulated longwall working face, illustrating the progressive development of caving, fracture propagation, and overburden compaction. Reproduced from Liu et al. (2026)

4 Evolution and applications of distributed acoustic sensing in mine geotechnical monitoring

Historically, mine geotechnical teams have been cautious about DAS technology for routine monitoring because early systems were relatively expensive, generated large data volumes, often difficult-to-interpret, therefore often not suited for practical geotechnical interpretation. Over the last several years, however, advances in interrogator design, fibre types and deployment methods, and processing workflows have contributed to broader adoption. Current DFOS platforms can be found in more compact, lower power, and lower cost per monitored metre than earlier generations, which can support more practical deployment of permanent or semi-permanent systems in mines.

In parallel, another important improvement in DAS technology is the reduction in effective noise floor and the corresponding increase in usable dynamic range (Figure 7). In practical terms, this means modern DAS can resolve weaker strain rate signals that previously would have been masked by instrument noise or operational background noise. For mining applications, this is associated with improved sensitivity to small microseismic events and blast-related responses, while also increasing confidence in the continuity of the recorded wavefield along the full instrumented borehole or drift. Recent studies have shown that DAS can complement conventional seismic systems by increasing spatial sampling density and, in some workflows, improving event detection and location precision when combined with geophones or accelerometers (Dande et al. 2024; Lellouch et al. 2020). Furthermore, detection methods specifically developed for DAS can leverage waveform coherence across densely sampled fibre channels to identify events without dependence on conventional geophone-based triggering, with Porras et al. (2024) demonstrating approximately twice as many detections as a standard approach on a 24-hour microseismic dataset.

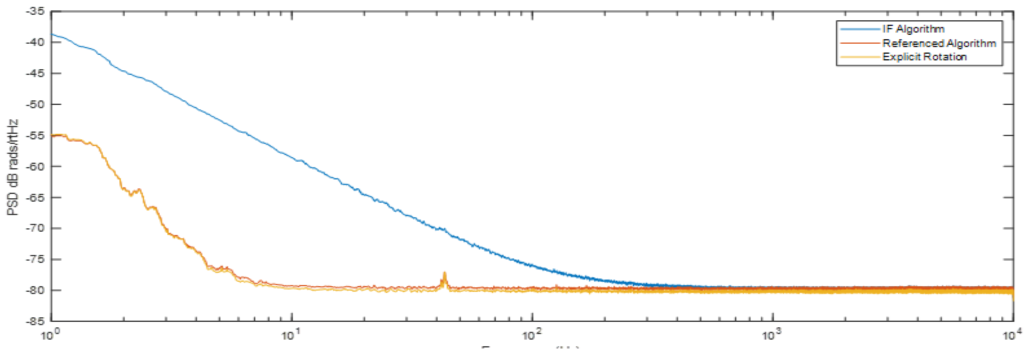


Figure 7 Noise performance of ONYX *peta* distributed acoustic sensing unit, at lower-frequency range

While DAS is primarily used for microseismic monitoring in mining and caving applications, another key application is its low-frequency capability where it is well established in hydraulic fracturing applications for fracture geometry, identifying fracture opening and closing, and stress-shadow creation and relaxation (Jin & Roy 2017). This is particularly relevant in geotechnical monitoring because not all rock mass responses are impulsive. Some of the most operationally significant rock mass behaviours occur over longer time scales or appear as low-frequency strain rate changes, including progressive fracture development, stress redistribution after blasting or cave advance, and the movement of slow or partially aseismic structures. Although not mining-specific, Wang et al. (2023) describe low-frequency DAS signals associated with mixed-mode fault reactivation and slow or partly aseismic deformation processes during hydraulic fracturing, providing a relevant analogue for interpreting non-impulsive rock mass response.

Where conventional geophone arrays provide discrete point measurements of particle velocity, DAS provides densely distributed measurements of axial strain or strain rate along the fibre, potentially capturing spatially continuous response over a broader section of the rock mass. Recent mining studies have highlighted DAS low-frequency response as a useful indicator of stress-related rock mass behaviour alongside microseismic monitoring (Furlong & Anderson 2022), and a recent underground mining case study explicitly analysed a 1–10 Hz DAS band for strain processing in parallel with a >10 Hz band for microseismic processing (Dande et al. 2024).

This lower-frequency capability is of value in rock mass response monitoring, since geotechnical hazards are not always expressed as discrete seismic events. In some cases, the rock mass responds through gradual deformation, intermittent slip, or evolving damage that may produce weak, spatially distributed, or partly aseismic signals. DAS can be sensitive to this type of response as it samples continuously along the fibre, allowing measurements of strain response, migration over time, and whether activity is localised or spatially distributed.

In summary for mining and rock mass monitoring applications DAS can provide higher-frequency microseismic waveform arrivals for event detection and location; lower-frequency response associated with blasting, cave advance, and stress redistribution; and spatially distributed strain rate patterns that may indicate gradual damage accumulation, geological structure activation, or yielding zones. This broader monitoring capability makes DAS an increasingly practical platform for rock mass response monitoring.

Most DAS units can interrogate 10s of kilometres of fibre-optics cable. Most mining geotechnical deployments, however, do not require the 50–100 km coverage typical of linear infrastructures such as pipelines or perimeters. In block caves or mining applications, the aim to continuously assess rock mass response within the mining zone, often ranging from hundreds of metres to a few kilometres, depending on the monitoring objective and fibre placement (e.g. boreholes, drifts, small-scale monitoring in zones with geotechnical concerns).

As a result, an optimal DAS interrogator for these mining contexts is typically characterised by 4 practical requirements:

- small footprint (minimal rack space and low weight)
- low power demand (compatible with remote power, solar/uninterruptible power supply (UPS), or low-voltage site huts)
- short-range optimisation (commonly <20 km fibre coverage per unit)
- operational simplicity (remote access, automated setup, and reduced maintenance).

Figure 8 shows an example of a compact DAS interrogator designed for shorter-range underground mining applications. These units employ a quantitative, phase-based sensing platform capable of monitoring fibre lengths of up to 20 km, all housed within a standard 19-inch, 1U enclosure. They provide fully coherent phase measurements with an approximate spatial resolution of 3 m. The low mass (approximately 6 kg), modest power consumption (<40 W), and passively cooled architecture make these systems suitable for deployment in underground or remote mining environments.

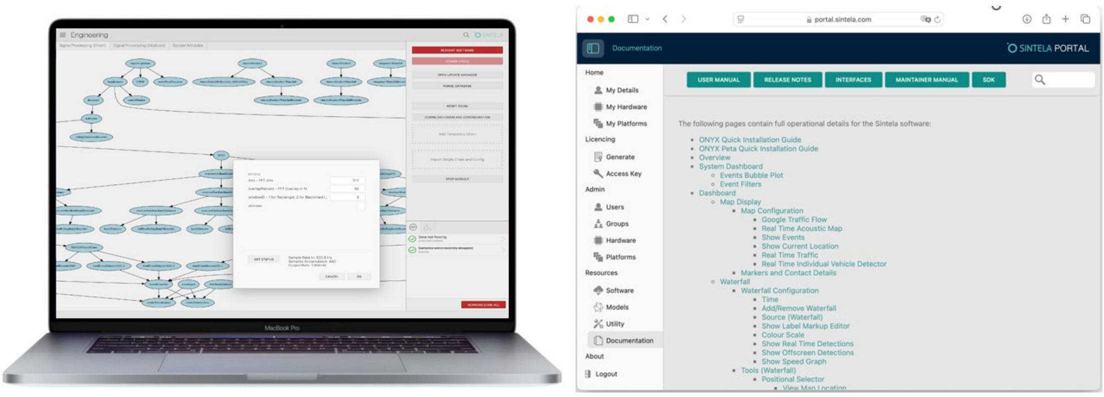
(a) (b)

Figure 8 An example of (a) a small footprint Onyx *nano* distributed acoustic sensing (DAS) for short- range applications such as underground deployment, and (b) Onyx *peta* DAS

For mine operations, an important consideration is whether DFOS measurements can be processed into interpretable outputs for rock mass response analysis within operationally relevant timeframes. The utility of a DFOS platform therefore depends not only on sensing performance, but also on the workflow used to convert raw measurements into strain, seismic, and diagnostic outputs that can be integrated with existing geotechnical datasets and reviewed in relation to mining activity. Furthermore, its practical value is enhanced when the strain and seismic outputs can be integrated into existing mine geotechnical platforms and workflows, allowing data to be visualised and assessed in real time in relation to mining activities and other geological and geotechnical datasets, with the aim of identifying evolving rock mass response and detecting potential hazards. To date, many mining deployments have remained at pilot-scale, and continued development in processing and visualisation remains important for broader operational use. The next section examines some recent developments in DFOS processing, visualisation, and interpretation that are improving its operational applicability for rock mass monitoring in mining and block caving operations.

5 Data visualisation and analysis

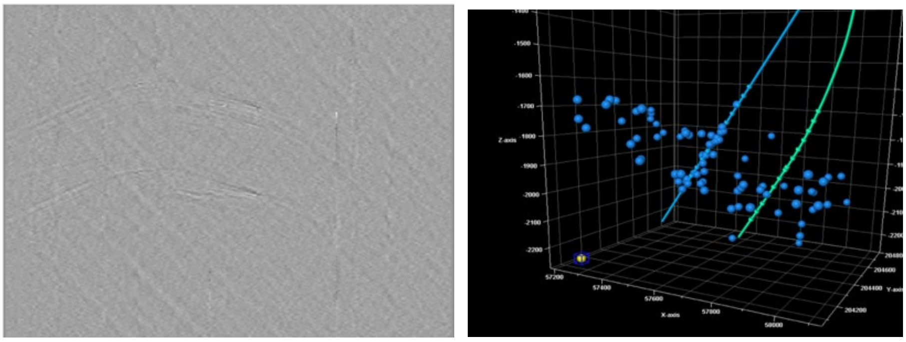
As DFOS platforms become more widely adopted for routine and autonomous monitoring across multiple industries, the development of accessible, operationally relevant dashboards has become an important requirement. These interfaces must present processed data in a form that supports interpretation, alerting, and decision-making by technical users who may not be specialists in fibre-optic sensing. In mining, DFOS dashboard capability has improved in recent years. Modern platforms increasingly provide web-based user interfaces with configurable visualisation tools, remote processing workflows, and API connectivity for integration with external systems (Figure 9). Rather than relying solely on centralised post-processing, advanced architectures can also support parallel processing chains configured directly on the sensing hardware, enabling real-time filtering, feature extraction, and export in multiple formats (e.g. raw, FBE, SEG-Y, HDF5) for downstream analysis in standard seismological or geotechnical software. By integrating acquisition, configuration, processing, and visualisation within a single environment, these platforms may reduce the barrier to DFOS adoption and make the technology more accessible to non-specialist users. Most advanced DFOS dashboards now have built-in diagnostics and fibre-quality characterisation, which enables remote assessment of system health.



(a) (b)

Figure 9 (a) Graphical ‘processing chain’ for processing raw data; (b) Web-access portal provides access to multiple users settings

In geoscience related applications, microseismic detection using DAS has also advanced in recent years. DAS dashboards can incorporate event detection and classification algorithmics, some using machine-learning models trained on large, labelled datasets. Machine-learning-based classifiers can provide automated event detection using a continuously expanding library derived from real site data (Figure 10.)



(a) (b)

Figure 10 Distributed acoustic sensing (DAS) edge processed microseismic detection. (a) Raw DAS data containing microseismic event and noise; (b) Seismic event location

From an integration perspective, the availability of gRPC and REST APIs allows DFOS dashboards to interoperate with external monitoring platforms and automated control systems, enabling fibre-optic data streams to be incorporated into broader mine operations and geotechnical workflows. For more computationally intensive tasks, containerised replay and reprocessing tools can support offline or cloud-scale workflows, which allows users to evaluate signal characteristics, test alternative processing chains, and validate machine-learning models using historical datasets. Collectively, these software functions support more efficient handling of DFOS datasets and may improve the feasibility of integrating fibre-optic measurements into broader geotechnical interpretation workflows for underground mining and block caving applications.

DAS-specific microseismic processing has also advanced in recent years. One example is RockSigma's Vinnova-funded project, Next Generation Microseismic Processing for Distributed Acoustic Sensing Data, which developed and validated a workflow for DAS-based microseismic event detection and location. Reported outcomes indicate full-scale mine validation of the workflow and demonstrate its applicability to continuous monitoring datasets in block caving environments (Vinnova 2025). Figure 11 shows an example of clustered seismicity located over several months of continuous DAS monitoring at a cave operation.

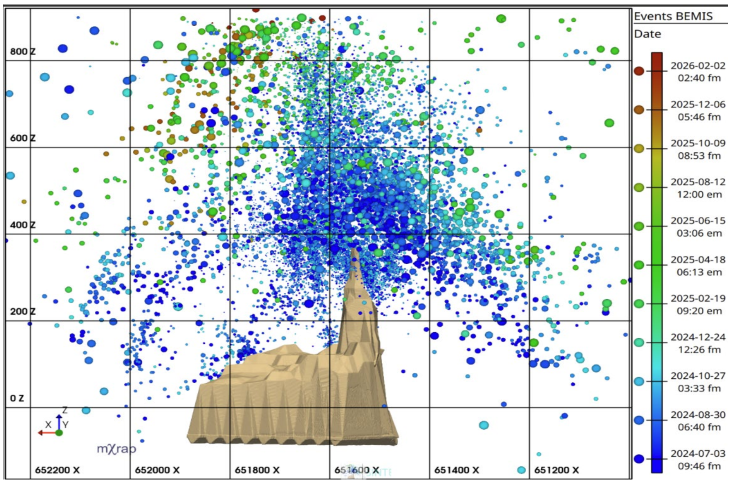


Figure 11 Cluster of microseismic data located on fibre-instrumented boreholes and acquired on distributed acoustic sensing at a caving operation, courtesy of RockSigma

In parallel with the development of DAS microseismic workflows, real-time DSS strain processing and 3D visualisation for fibres installed in deep boreholes are also advancing. These systems can stream distributed strain profiles, distinguish tensile from compressive response, and render their spatial and temporal evolution along multiple boreholes to support identification of developing deformation features within the monitored rock volume (Figure 12). This capability is particularly important in caving applications, where progressive micro strain trends may indicate fracture initiation and propagation in advance of cave breakage. Real-time visualisation and cross-borehole correlation of strain evolution within and around the cave can therefore provide a practical tool for constraining cave-back geometry and interpreting cave propagation under varying geological structures and stress regimes.

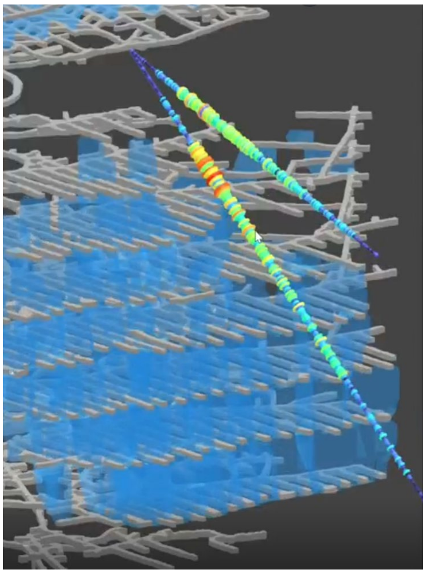


Figure 12 Conceptual visualisation of real-time distributed strain sensing strain data along 2 deep boreholes in an underground mine

In summary, the practical value of a DFOS platform for rock mass monitoring depends heavily on the availability of a geotechnical dashboard that converts raw measurements into timely, interpretable outputs for operational use. These outputs may include seismicity, distributed strain, system diagnostics, and, over time, other potential output such as automated tomography, evolving strain-based hazard maps, and seismic hazard visualisation. As these capabilities mature and become better integrated with mine geotechnical workflows, DFOS is becoming a more practical platform for routine interpretation and decision support in underground mining and block caving operations.

6 Field application: distributed acoustic sensing and distributed strain sensing in cave monitoring

The performance of a DFOS-based rock mass monitoring program depends not only on the sensing technology, but also on the overall monitoring system design and implementation. In practice, reliable long-term strain and acoustic measurements require consideration of interrogator selection and configuration; fibre-optic cable specification and installation methods suited to the geotechnical and operational environment; coupling and survivability; and data processing and integration workflows. Where these elements are treated independently or added without a coherent design basis, the resulting system may provide limited interpretive value despite successful data acquisition.

This section provides a brief discussion of the implementation of an integrated DAS/DSS platform in block cave operations, focusing on system geometry, preliminary observations, and design principles for long-term monitoring. The discussion is necessarily limited to a case study in which the authors were directly involved in the system design and deployment. Additional underground mining deployments are currently in progress, but the corresponding data and results were not available for inclusion at the time this paper was prepared, as initially planned.

DAS is commonly applied for mine microseismic monitoring by grouting fibre-optic cable in deep boreholes around the cave footprint. For improved 3D microseismic coverage, (not strain and cave back) and durability through cave growth, 'microseismic monitoring' boreholes should be positioned where deformation and stress-driven damage to the borehole/cable are least likely. A minimum of 3 boreholes with varied orientations, combined with toe turn-arounds (daisy-chain layouts), generally improves azimuthal coverage and event location accuracy, while providing long-term monitoring, although if available more boreholes can be instrumented depending on the cave geometry and access.

DAS provides dense spatial sampling and continuous coverage across the cave volume, including zones where deployment of conventional geophones is impractical. Figure 13 illustrates microseismic clusters detected with DAS during cave propagation. Although the borehole layout was not optimised for DAS (microseismic monitoring was not the primary objective), the system still captured induced seismicity. Some mirrored locations were observed, highlighting the importance of purpose-designed geometry when DAS is deployed as the primary seismic monitoring system. A companion paper in these proceedings (Furlong & Anderson 2026) provides a detailed DAS–geophone comparison.

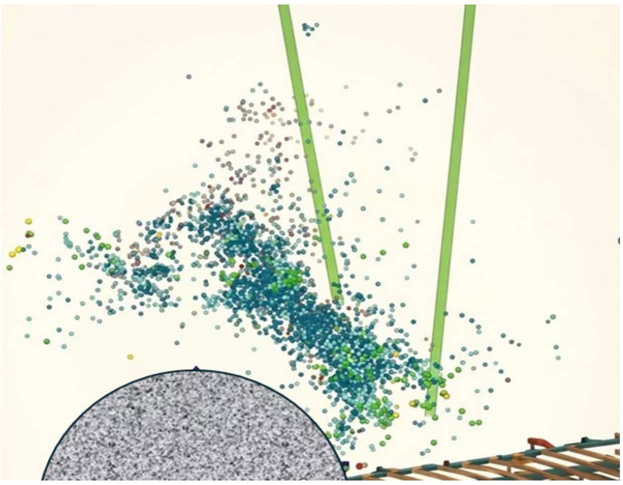
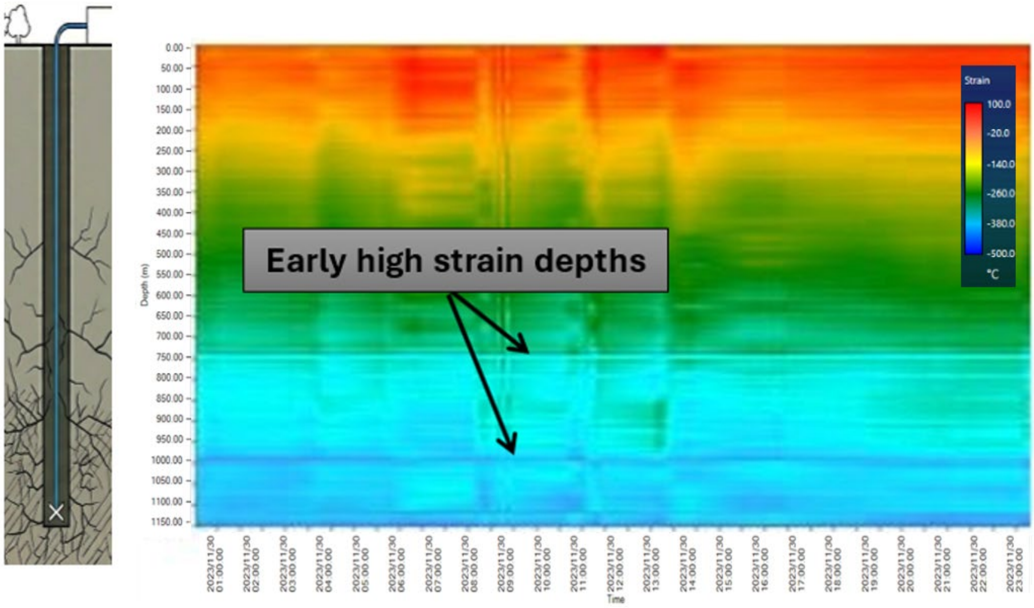


Figure 13 Anonymised image. Cross-section of a block cave operation showing seismic clusters acquired on distributed acoustic sensing over a few weeks. Green lines show the 2 fibre-instrumented boreholes

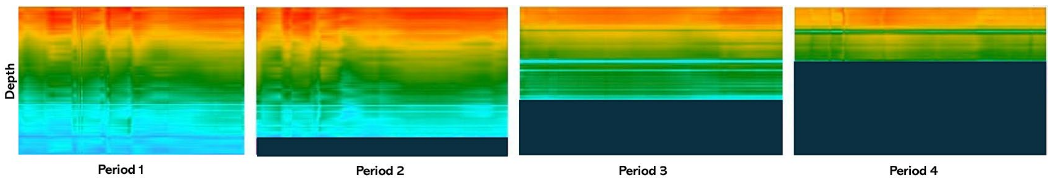
In addition to DAS, DSS has been applied to deformation monitoring in underground mines and block cave operations. In these applications, fibre-optic cables are installed in deep boreholes within the cave zone to monitor distributed strain evolution over time. Where fibre breakage occurs as the cave propagates, measurements can continue along the remaining intact section of the fibre, allowing strain concentration and subsequent breakage progression to be tracked spatially.

For DSS applications, often one unit of interrogator can monitor multiple boreholes in close intervals by switching from one borehole to the next to complete a strain reading. For an overview of DAS and DSS comparison, see Anderson & Parker 2024.

Figure 14 demonstrates early indications of fracture development at certain depths along a borehole fibre measured by DSS at a block cave operation. Over months of monitoring, DSS captures micro strain-level strain accumulation concentrated at specific depths, which later become the failure (break) points. After each break, the strain concentration reappears at a shallower depth, indicating the next failure depth as the cave back propagates.



(a)



(b)

Figure 14 Distributed strain sensing waterfall plots showing the evolution of strain along the fibre depth (y-axis) over time (x-axis). (a) Highlights 2 depths along borehole where early signs of fracturing/failure start to appear; (b) Anonymised strain waterfalls showing progressive accumulation of strain from left to right over 12 months, with each plot showing one day of strain accumulation at certain depths

Multiple DAS and DSS deployments in underground mining and caving operations have provided case study evidence relevant to the interpretation of rock mass response and cave growth. DFOS layouts designed for block caving can support estimation of cave-back geometry through progressive cable breakage along fibre-instrumented boreholes. Following breakage, the remaining intact fibre may continue to provide distributed strain measurements, allowing ongoing monitoring as cave propagation continues. With multiple boreholes, these observations can be spatially combined to estimate cave-back position and its temporal evolution, and to support interpretation of yielded, seismogenic, and more competent rock mass domains.

For integrated DAS/DSS monitoring, cave-front progression can be inferred by combining early strain transients captured by DSS (at micro strain-scale resolution) with low-frequency DAS strain rate measurements (Anderson & Parker 2024). This integrated approach enables a more detailed characterisation of rock mass response across the transition from yielded to seismogenic regions, while also providing insight into how rock mass properties and geological structures influence the geometry and rate of cave propagation. In the case presented here, fibre-optic cables installed in 2 boreholes were interrogated using both DAS and DSS to capture distributed dynamic and quasi-static strain measurements.

Lastly, DAS-based microseismic monitoring provides dense event detection and improved spatial definition of microseismic clusters, helping delineate the evolving seismogenic zone using the same fibre infrastructure deployed for strain monitoring. Where feasible, installing select fibres in permanent boreholes outside the future cave footprint can extend array longevity. In the example above, DAS was detecting cluster of low-magnitude seismic events, indicating the yield zone, and further above recording higher-magnitude seismic events that were indicative of seismogenic zone and to some degree defining the shape of the cave back. Fibre-instrumented boreholes provide a practical means of obtaining continuous distributed measurements in locations where deployment of conventional geophones may be constrained by access, geometry, or installation complexity.

Experience with DAS/DSS deployment in caving operations, while still limited, has provided valuable insights and highlights the need for DFOS system designs to be tailored to site-specific conditions. Key improvements include optimised downhole cable configurations and installation methods to enhance both redundancy and spatial coverage. The use of turn-around configurations or bottom hole assemblies at the borehole toe extends the effective fibre length and improves DAS coverage. In some cases, multiple cables can be installed within a single borehole to provide redundancy in the event of fibre breakage. Fibre deployment in deep boreholes has become increasingly routine, with installation procedures adapted to align with drilling equipment and site constraints. Experience from recent deployments indicates that DFOS implementation in caving operations benefits from optimisation of cable configuration, borehole layout, and installation procedures to improve redundancy and spatial coverage. Turn-around configurations or bottom hole assemblies can extend effective fibre length and increase DAS coverage, while multiple cables within a single borehole may provide redundancy where fibre breakage is expected. In addition, lower-power interrogator architectures and local processing approaches may simplify underground deployment and support more timely review of strain and microseismic outputs.

Looking forward, integrated DAS/DSS systems have the potential to support caving monitoring and interpretation workflows. Emerging capabilities include automated tomographic imaging, continuous 3D mapping of cave-back geometry, and enhanced resolution of rock mass domains, including elastic and transitional zones. The integration of distributed strain and seismic data further enables the development of spatially resolved hazard maps and provides critical constraints for calibrating numerical models of cave propagation. Additionally, surface-deployed fibre arrays over the cave footprint offer early detection of subsidence trends, and risk management.

The schematic in Figure 15 below illustrates a conceptual fibre-cable layout for a caving operation. Boreholes drilled within the planned cave volume are treated as consumable installations and are used to track strain evolution and cave-back propagation, whereas boreholes located farther from the cave footprint, in more competent rock, are installed for longer-term microseismic monitoring. In the consumable array, fibre is intentionally allowed to fail as the cave advances, while monitoring continues along the remaining intact sections, providing spatial constraints on cave-back position and the development of yielded zones. In parallel, the permanent fibres in stable ground provide continuous observations of microseismicity and strain rate response. Together, these complementary layouts enable distributed, three-dimensional characterisation of cave evolution, supporting delineation of elastic, seismogenic, and yielded domains in near real time using a single integrated sensing system.

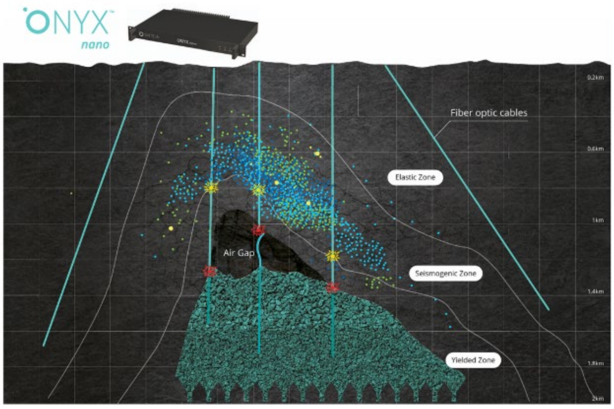


Figure 15 Schematic illustration of a multi-borehole distributed fibre-optic sensing monitoring layout, for a distributed 3D characterisation of cave evolution, defining elastic, seismogenic, and yielded zones in real time using a single integrated sensing system

7 Future developments

DFOS is increasingly being investigated as a method for continuous, high-spatial-resolution rock mass response monitoring. Current development priorities include improved fibre geometry design, commissioning and calibration procedures, integration of DAS and DSS outputs, and 3D visualisation tools that link DFOS observations with mine geotechnical platforms and monitoring systems. Based on field experience, near-term development priorities include:

- objective-driven fibre geometry design (seismic aperture, strain coverage, survivability)
- commissioning and DAS/DSS selection, settings and calibration based on monitoring objectives
- integrated DAS/DSS outputs (e.g. strain localisation and trends, event-rate changes, microseismic activity and analysis)
- 3D visualisation and analysis platform that link near real-time DFOS observations, such as distributed strain, seismicity and hazard maps into mine operations and geotechnical models
- operational integration: automated exports, reports and alerts into site geotechnical monitoring platforms to strengthen trigger action response plans (TARPs) and proactive decision-making.

Longer-term research directions include the identification and validation of precursor signatures associated with cave initiation and propagation, the development of stress and energy inversion processes using integrated DAS/DSS data, and the adaptation of passive imaging, ambient noise tomography, and time-lapse interferometric techniques, successfully applied in other geophysical fields, to resolve mine scale rock mass response, damage initiation, fracture network development, and stress/strain trajectories in caving environments.

8 Conclusion

Distributed fibre-optic sensing appears most effective in underground mining and caving applications when implemented as a dedicated rock mass monitoring platform. When appropriately designed and configured, integrated DAS and DSS can capture ground response, microseismicity and strain signals alongside lower-frequency events, providing continuous spatial context that can be difficult to achieve with point instruments or traditional geophones alone.

Field experience indicates that the key factors influencing performance are not only the interrogator specifications, but the deployment design and the workflow that converts raw measurements into geotechnical decisions. Important considerations include fit-for-purpose cable selection and deployment, with redundancy for boreholes likely to be consumed by cave growth, commissioning/QC practices that establish calibrated strain and seismic baselines, and visualisation platforms that integrate into existing mine geotechnical workflows.

Looking forward, further development should prioritise the validation of precursor signatures associated with cave initiation and propagation, the establishment of repeatable and scalable interpretation workflows for cave-front tracking and three-dimensional mapping of cave evolution, and tighter integration of DFOS-derived hazard indicators with site seismic systems and risk management protocols, including TARPs. In parallel, advances in automated tomography, passive imaging, and time-lapse interferometric analysis may provide a pathway toward resolving stress redistribution, damage evolution, and stress-path trajectories at mine scale.

Continued progress in system design, data integration, and operational workflows is likely to determine the extent to which DFOS can move beyond trial deployments and become a routine component of geotechnical monitoring in caving environments.

Use of artificial intelligence disclosure statement

In the preparation of this work, the authors used M365 Copilot (Basic) to research relevant publications and to improve the language and clarity of writing of the paper. The authors have reviewed the content and edited it where required and take full responsibility for said content.

References

Anderson, Z & Parker, 2024, 'Rock mass response monitoring in deep mining using DAS and DSS systems', *Proceedings of the 9th International Conference and Exhibition on Mass Mining*, Luleå University of Technology, Luleå, pp. 1583–1593.

Bao, X, Zhou, Z & Wang, Y 2021, 'Distributed time-domain sensors based on Brillouin scattering for temperature, strain and acoustic wave detection', *PhotoniX*, vol. 2, p. 14.

Chambers, D & Shragge, J 2023, 'Seismoacoustic monitoring of a longwall face using distributed acoustic sensing', *Bulletin of the Seismological Society of America*, vol. 113, no. 4, pp. 1652–1663.

Chambers, D, Shragge, J, Griffin, L, Pevzner, R & Urosevic, M 2025, 'Distributed acoustic sensing for longwall coal mines', *International Journal of Rock Mechanics and Mining Sciences*, vol. 189.

Dande, S, Forbes, E, Butler, T, Graham, K, Hawryluck, C, Hall, A … Cherubini, A 2024, 'Utilising distributed acoustic sensing for monitoring rock mass stress conditions in underground mining: a case study', in P Andrieux & D Cumming-Potvin (eds), *Deep Mining 2024: Proceedings of the 10th International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 375–390, https://doi.org/10.36487/ACG_repo/2465_19

Furlong, J & Anderson, Z 2022, 'Distributed acoustic sensing/distributed strain sensing technology and its applications for block cave progress monitoring, rock mass preconditioning, and imagining', in Y Potvin (ed.), *Caving 2022: Proceedings of the Fifth International Conference on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 991–1006, https://doi.org/10.36487/ACG_repo/2205_68

Fernández-Ruiz, MR, MR, Costa, L, Martins, HF, Martin-Lopez, S, González-Herráez, M & Pastor-Graells, J 2020, 'Distributed acoustic sensing for seismic activity monitoring', *APL Photonics*, vol. 5, no. 3, p. 030901.

Jin, G & Roy, B 2017, 'Hydraulic-fracture geometry characterization using low-frequency DAS signals', *The Leading Edge*, vol. 36, no. 12, pp. 975–980.

John, D & Hoehn, K 2024, 'Distributed fibre optic sensing for ground monitoring in underground hard rock mining', in P Andrieux & D Cumming-Potvin (eds), *Deep Mining 2024: Proceedings of the 10th International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 391–402, https://doi.org/10.36487/ACG_repo/2465_20

Lalam, N, Lu, P, Buric, MP & Ohodnicki, PR 2019, 'Distributed optical fibre sensing: review and perspective', *Applied Physics Reviews*, vol. 6, no. 4.

Lellouch, A, Lindsey, NJ, Ellsworth, WL & Biondi, BL 2020, 'Comparison between distributed acoustic sensing and geophones: downhole microseismic monitoring of the FORGE geothermal experiment', *Seismological Research Letters*, vol. 91, no. 6, pp. 3256–3268.

Lellouch, A & Biondi, BL 2021, 'Seismic applications of downhole distributed acoustic sensing', *Sensors*, vol. 21, no. 9, article 2897.

Lellouch, A, Schultz, R, Lindsey, NJ, Biondi, BL & Ellsworth, WL 2021, 'Low-magnitude seismicity with a downhole distributed acoustic sensing array—examples from the FORGE geothermal experiment', *Journal of Geophysical Research: Solid Earth*, vol. 126, no. 1, article e2020JB020462.

Liu, X, Zhang, Z, Li, S, Wang, Y & Chen, X 2026, 'Application of distributed fibre optic sensing in mining pressure and overburden monitoring in three-dimensional similarity simulation experiments', *Frontiers in Earth Science*, vol. 14, 1756693.

Lu, P, Lalam, N, Badar, M, Liu, B, Chorpening, BT, Buric, MP & Ohodnicki, PR 2019, 'Distributed optical fiber sensing: review and perspective', *Applied Physics Reviews*, vol. 6, no. 4, p. 041302

Nowak, S, Lato, M, Diederichs, MS, Hutchinson, DJ & Kalenchuk, KS 2024, 'Geomechanical monitoring of an underground bulk mining operation using distributed fibre strain sensing', *Mining, Metallurgy & Exploration*, vol. 41, pp. 1553–1565.

Porras, J, Wuestefeld, A, Hopp, CJ & Bruhn, D 2024, 'A semblance-based microseismic event detector for DAS data', *Geophysical Journal International*, vol. 236, no. 3, pp. 1716–1727.

Russell, SJ & Hill, DJ 2025, 'Distributed acoustic sensing: a real-world perspective, requirements, applications, and techniques', *Proceedings of the 29th International Conference on Optical Fiber Sensors*, Bellingham, vol. 13639, article 1363904.

Shao, L, Li, J, Zhang, Y, Wang, Z & Zhou, Z 2025, 'Artificial intelligence-driven distributed acoustic sensing technology and engineering application', *PhotoniX*, vol. 6, no. 4.

Shi, Q, Denolle, MA, Ni, Y, Williams, EF & You, N 2025, 'Denoising offshore distributed acoustic sensing using masked auto-encoders to enhance earthquake detection', *Journal of Geophysical Research: Solid Earth*, vol. 130, no. 2, e2024JB029728.

Wang, C, Eaton, DW & Ma, Y 2023, 'Numerical modeling of low-frequency distributed acoustic sensing signals for mixed-mode reactivation', *Geophysics*, vol. 88, no. 6, pp. WC25–WC36.

Williams, E 2023, *Monitoring Earthquakes and Ocean Waves with DAS Across Cook Inlet, AK*, video file, https://www.youtube.com/watch?v=Z0FgBI7Mbvc

Vinnova 2025, *Next Generation Microseismic Processing for Distributed Acoustic Sensing Data*, project report.