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Enhancing cave seismic monitoring with distributed acoustic sensing and template matching

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Abstract

Distributed acoustic sensing (DAS) is increasingly deployed in underground mining to support seismic monitoring due to its dense spatial coverage and flexible installation. Despite these advantages, the use of DAS for cave-front tracking has not yet been fully explored.

This study presents the application of a well-known seismological template-matching method to DAS data to improve the detection of weak, repeating seismic events associated with cave establishment firings. The approach relies on waveform templates selected from previously identified events and applies them to continuous DAS records to search for similar signals, including weak events that may be missed by standard detection procedures used in conventional underground geophone arrays. By increasing the number of detected events, the approach enhances the effective spatial resolution of microseismic observations in the cave environment.

The workflow is demonstrated using DAS data acquired during active cave development at an underground mining operation. The results show that the method increases the number of detected events and better defines the seismicity pattern associated with cave establishment firing. The resulting catalogue provides a clearer view of the rock mass response to mining and supports more reliable cave-tracking interpretation.

Overall, the results demonstrate that template matching can substantially extend the practical capability of DAS-based microseismic monitoring for cave-tracking applications. The approach integrates with existing monitoring workflows and adds value without requiring changes to acquisition geometry or hardware.

Keywords: *distributed acoustic sensing, template matching, seismic monitoring, cave front tracking*

1 Introduction

Distributed acoustic sensing (DAS) converts a standard telecommunication optical fibre into a dense array of quasi-continuous strain or strain-rate measurements. An interrogator sends coherent laser pulses into the fibre and infers axial strain from phase changes in backscattered light over a chosen gauge length (Hartog 2017). With metre-scale channel spacing, a single cable can provide thousands of sensing points and form a large-N aperture that samples wavefields at a spatial density that is unfeasible for conventional geophone arrays.

In underground cave mining, seismic monitoring is a key tool for observing how the rock mass responds to development and production. The spatio-temporal patterns of seismic activity are used to understand cave growth, determine the position of the cave front, identify seismogenic structures and guide operational decisions such as exclusion protocols and hazard management. These interpretations rely on significant events that can be robustly located as well as high-rate populations of weak events that illuminate evolving damage and stress redistribution close to the cave.

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Conventional underground seismic systems based on sparse geophone arrays generally provide reliable locations and source parameters for events above the network detection threshold, but in many cave settings, most signals for cave establishment and early growth are weak and easily masked by blasting, machinery and other underground activity, meaning they can remain undetected or unclassified in routine workflows. DAS can complement these arrays by providing dense spatial sampling of coherent waves, which can then be stacked across many channels to improve detectability. However, using DAS in practice is not straightforward: it records directional strain along the fibre, coupling varies along the cable, and the data volume is huge. Therefore, detection should focus on waveform similarity and cross-channel coherence rather than only on simple energy triggers such as STA/LTA (short-time average to long-time average).

Template matching correlates representative event waveforms (templates) against continuous recordings to detect repeating signals that may be invisible in raw data. When applied to large-N arrays, such as DAS, it can push the detection limit well below the noise level by combining correlation evidence over many channels. In seismology, matched filtering has been widely used to detect repeating earthquakes, low-frequency events, aftershocks and induced seismicity, and has been shown to outperform traditional triggering for low SNR signals in non-stationary noise (Gibbons & Ringdal 2006; Shelly et al. 2007; Li & Zhan 2018, Herrmann et al. 2019; Ross et al. 2019).

This paper adapts and tests template matching for underground DAS data acquired during active cave development. The objectives are to detect additional weak events associated with cave establishment firings, expand the event catalogue for cave-tracking interpretation, and document a workflow that can be integrated with existing seismic monitoring systems. The paper also highlights the strengths of the approach for weak, repeating events and its limitations related to template bias, computational cost and quality control.

2 Template-matching workflow for distributed acoustic sensing

In routine underground seismic monitoring, simple energy triggers such as STA/LTA are common, but in an active mine, the noise level changes constantly, so sensitive thresholds often produce many detections that later turn out to be noise. Template matching is more targeted for repeating events because it checks whether the waveform resembles a known example, rather than only whether the signal is large enough. With DAS, correlation can be computed on many channels and then stacked, so a real repeating event can still stand out even if it is hard to see on a single or a few geophones. The method has practical limitations: it mainly detects events similar to the template catalogue; running many templates on long continuous data is computationally expensive, and some narrowband or repetitive noise can still produce false matches unless thresholds and quality control are robust. In practice, the workflow relies on a well-defined template set, consistent preprocessing (gauge length selection, optional downsampling, waveform filtering) and sensible channel selection with normalised correlation.

Let $x(i)t$ be the continuous strain-rate signal on DAS channel i and $yi(t)$ the template window for the same channel. For each channel, the normalised cross-correlation $CCi(\tau)$ is computed and then stacked over a selected set of channels to obtain a single detection trace $CC(\tau)$. A similar multi-channel stacking approach for DAS-matched filtering was used by Li & Zhan (2018). Events that are similar to the template produce a coherent correlation peak across many neighbouring channels, whereas random noise does not align between channels and is therefore suppressed by stacking. No threshold is directly applied to the raw correlation trace; instead a robust score $S(\tau)$ is used:

$$S(\tau) = \frac{CC(\tau) - median(CC)}{MED(CC)} \quad (1)$$

where $median(CC)$ is the median of $CCi(\tau)$ over the processed time window.

$MED(CC) = median(|CC(\tau) - median(CC)|)$is the median absolute deviation. Detections are declared at local peaks of $S(\tau)$ above a chosen threshold, with simple rules to avoid double-picking the same arrival or treating noise fluctuations as events.

Detections are split into two stages to create a single clean event list. First, within each template, peaks within a short window are combined by retaining the highest-scoring peak. Across templates, duplicate detections are common because multiple templates within a family can match the same target event; these duplicates are removed within a de-duplication window by retaining the detection with the highest score.

Quality control is essential, especially for weak detections that are not clearly visible on individual DAS channels. Quality control typically includes selecting a minimum number of channel participation at the detection peak, inspecting waveforms on representative channels to reject periodic or narrowband noise, and cross-checking detection times against a geophone catalogue, where available. In addition, 2D filtering can be used to improve SNR, but it is usually computationally expensive (Saad & Alkhalifah 2026).

3 Data acquisition

The workflow is demonstrated on DAS data acquired during active cave development at an underground mining operation in the Cadia mine. The optic fibre was installed in the 575 m borehole in the vicinity of the cave front and interrogated by Treble+ (Terra15) (Figure 1). The dataset comprises a 24-hour recording window surrounding a drawbell firing initiated at 6 am on 3 November 2025.

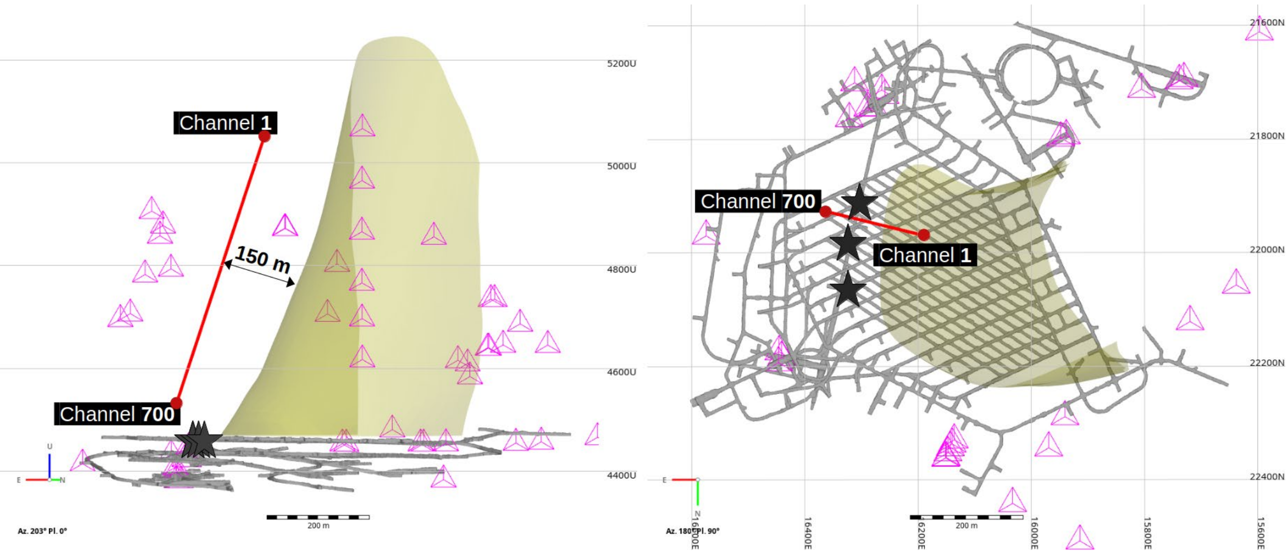

Figure 1 Layout of distributed acoustic sensing fibre (red line) and geophone array (magenta triangles). The drawbell firing location is marked by a black star

The DAS system recorded approximately 1,400 channels at ~1 m spacing along a fibre length of about 1 km. The fibre turnaround point was near channel 700, corresponding to the bottom of the borehole. The native sampling rate was 6.7 kHz. For processing, the strain-rate data were downsampled to 3 kHz after gauge length selection, and a subset of channels was analysed to control computational cost.

In parallel, a conventional underground seismic system based on geophones operated in the same period and provided a routine event catalogue. This catalogue was used for interpretation and validating that matched-filter detections were temporally and spatially consistent with cave-related seismicity. The geophone system also provided particle velocity waveforms used for source parameter estimation.

The DAS acquisition parameters are summarised in Table 1.

Table 1 Distributed acoustic sensing acquisition parameters

Parameter	Value
Number of channels	1,440
Channel spacing (dx)	0.82 m
Gauge length used	5 m
Fibre length	~1,200 m
Native sampling rate	6.76 kHz
Processed sampling rate	3 kHz
Measurement period	24 hours
Data volume (continuous)	~4.2 TB (raw)
Pulse rate	28.8 kHz
Pulse length	2.45 m
Fibre-optic cable	Tight-buffered tactical cable
Total seam file size	4.2 TB

4 Data processing

The matched-filter pipeline was configured to target weak events occurring immediately after the drawbell firing. Several gauge lengths were tested to optimise the detectability of these events. A 5 m gauge length provided the best balance, improving SNR while preserving coherent phase energy in the weak-event waveforms.

Templates were selected from the routine geophone-detected catalogue as high-quality waveforms with clear P-wave and S-wave onsets and consistent moveout along the fibre. Fifteen templates were used to represent the dominant repeating families in the dataset, spanning sources from the drawbell firing area to the top of the cave and covering most relevant azimuths and distances. Each template window was 0.21 s long, which was sufficient to capture both P-wave and S-wave energy (examples are shown in Figure 2). For matched filtering, the continuous strain-rate stream and the template windows were band-pass filtered to 60–800 Hz, consistent with the dominant frequency content of geophone-detected events. Processing used channels 30–700 with a step of 4 (i.e. every fourth channel, ~3.8 m spacing) to reduce computational cost; using a denser channel spacing did not significantly increase the number of detections but noticeably increased runtime and false (noise) detections. Assuming a typical multi-processor workstation and parallel processing of templates, the total processing time for this dataset, including velocity to strain-rate conversion, downsampling and template matching, is estimated to be approximately 20–30 hours. Peak picking and consolidation were set conservatively to prioritise high-confidence detections and stable behaviour under mine noise, using a detection threshold of $S \geq 9.5$ and a 0.15 s merge window to remove duplicate picks. Lowering the detection threshold significantly increased the number of spurious detections, which were commonly associated with channel-coherent instrumental noise rather than genuine seismic events or environmental mine noise.

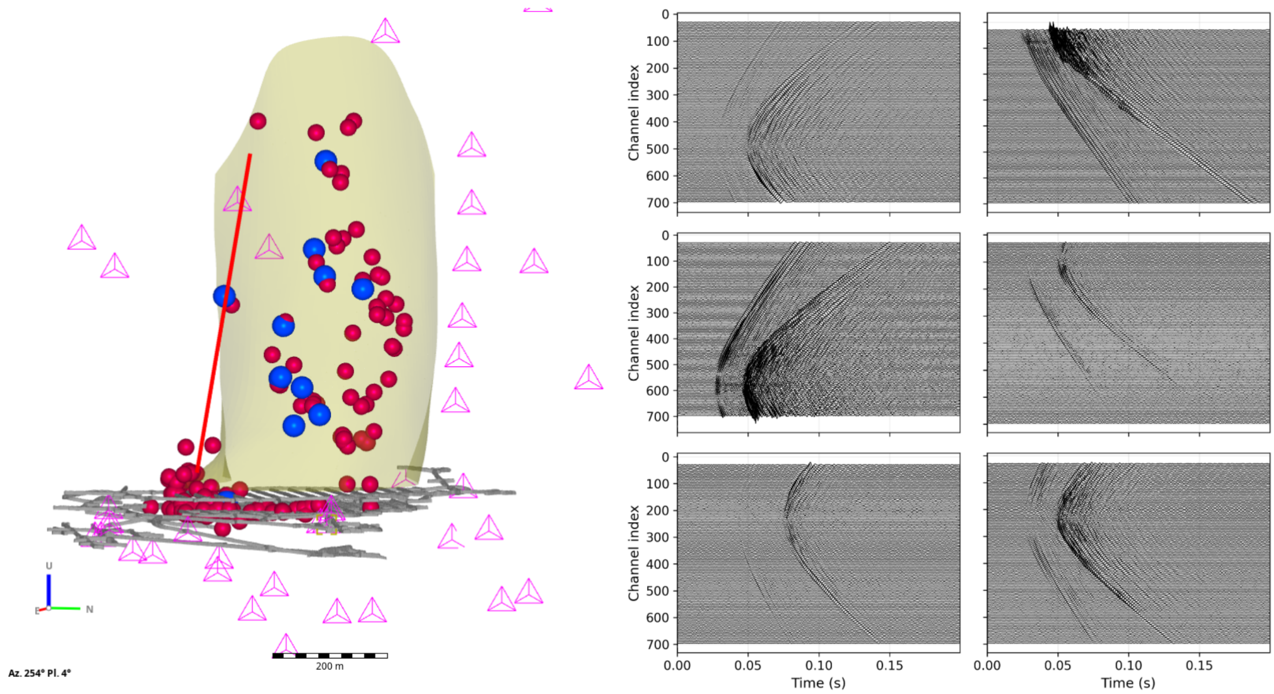

Figure 2 (a) All seismic events detected by the geophone network within 24 hours after drawbell firing, in the vicinity of the cave front (red), with the selected templates highlighted (blue); (b) Waveforms of six randomly selected templates. Distributed acoustic sensing channel 0 represents the borehole collar

After the detection stage, the DAS waveforms were merged with geophone array data. Where required, the corresponding time windows were extracted from the continuous geophone recordings and combined with the DAS traces to create a single-event dataset. Only geophones located close to the fibre were included in the merge. Incorporating geophone recordings was necessary to better constrain event locations, which can be ambiguous when using a single fibre alone. Event locations were then computed using the cross-correlation location (CCLoc) algorithm (Gal et al. 2021), and source parameters were finally estimated from geophone amplitudes.

5 Results

Across the analysed 24-hour window, routine geophone processing identified approximately 204 events associated with the drawbell firing sequence, most of them located near the drawbell area. Applying the matched-filter detector to the DAS data increased the number of detections to approximately 401, effectively doubling the catalogue for the same period (Figures 3 and 4). Most of the additional detections were weak events that routine trigger-based processing did not capture. Although many of these signals were difficult to recognise visually on individual DAS channels, they showed clear similarity to the selected templates in the correlation domain. Most of the additional DAS detections were located close to the fibre route, indicating that template matching is particularly effective for detecting weak repeating events in the near-fibre volume (Figure 4). This spatial sensitivity is consistent with the expected DAS response, which decreases with source distance.

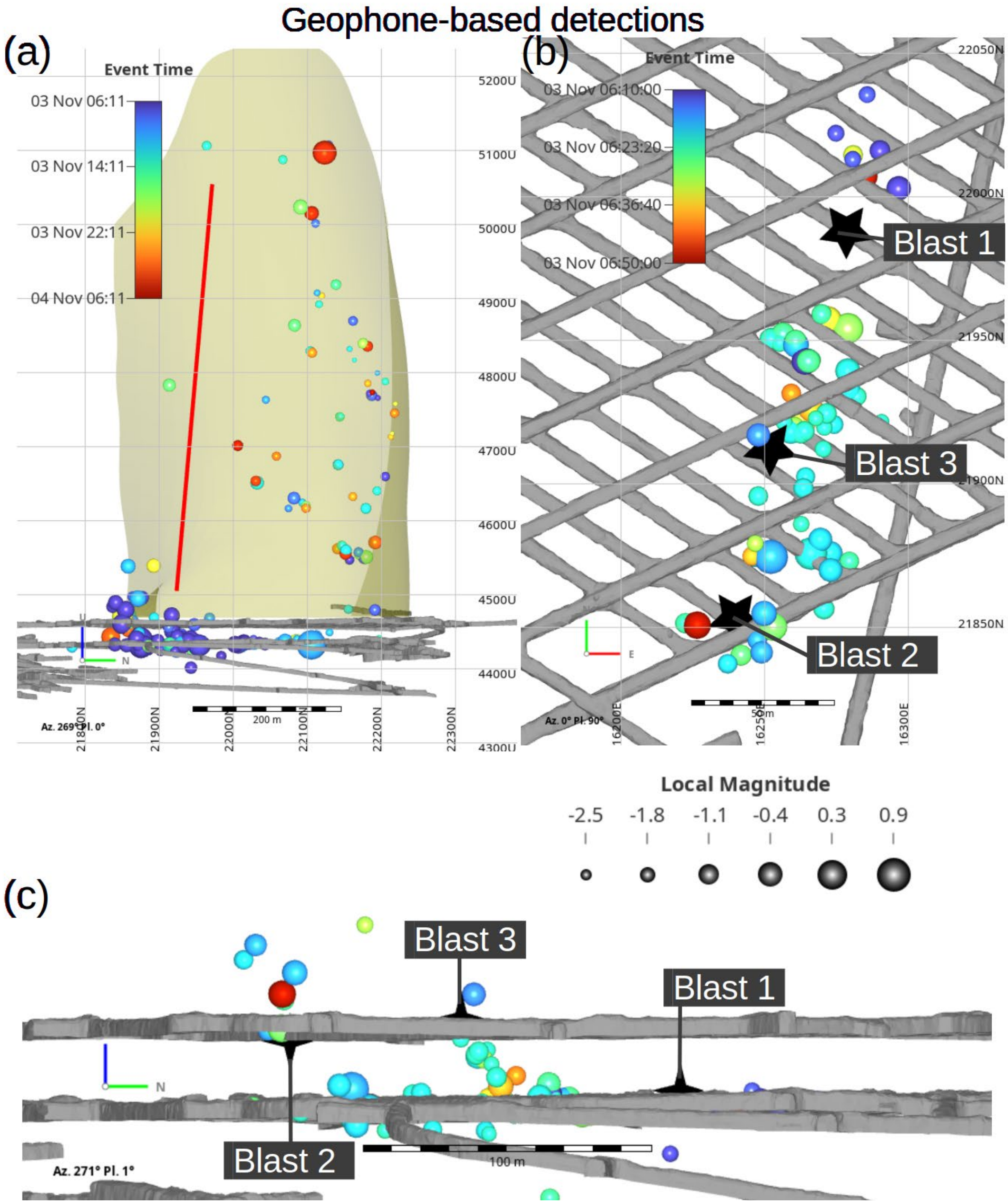

Figure 3 **(a) Seismic events detected by geophones within 24 hours after drawbell firing in the vicinity of the cave front; (b and c) Seismic events that occurred within 40 minutes of the major blasts**

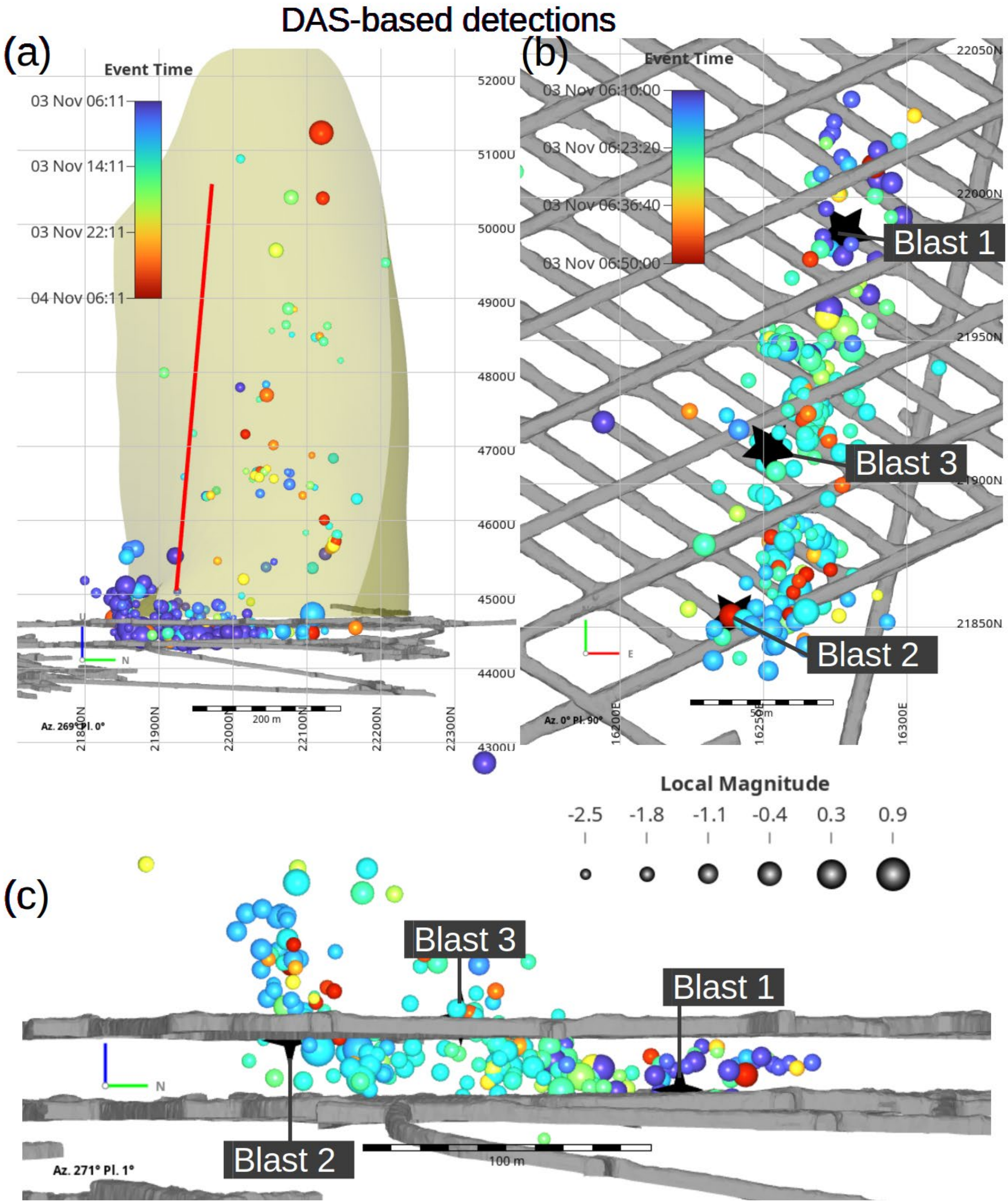

Figure 4 **(a) Seismic events detected by distributed acoustic sensing within 24 hours after drawbell firing in the vicinity of the cave front; (b and c) Seismic events that occurred within 40 minutes of the major blasts**

A comparison with the geophone-detected catalogue shows that the two systems are sensitive to different parts of the monitored volume. Figure 5 presents the geophone array sensitivity in relation to the cave geometry. Two zones (Zones 1 and 2) show increased geophone capability to detect weaker events. Zone 2 is located more than 300 m from the fibre, and DAS detections there are sparse, suggesting that attenuation strongly limits DAS sensitivity to weak events at this distance. In contrast, in Zone 1, where the geophones and the fibre are both located at a similar distance from the drawbell firing area, the DAS catalogue shows a clear improvement in detection capability. This confirms that template matching significantly improves DAS sensitivity, but mainly for weak events in the near-fibre volume, where detection of events around magnitude −2.0 is most effective.

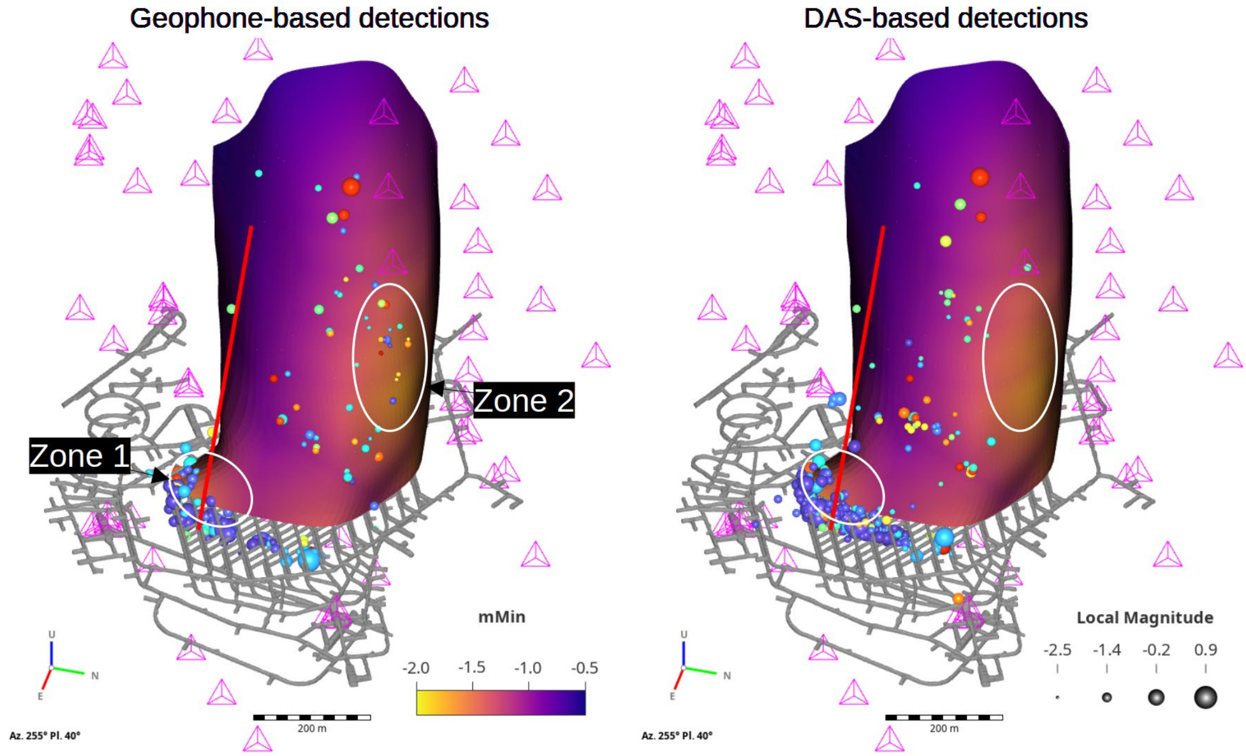

Figure 5 Sensitivity of geophone array with events detected: (a) By distributed acoustic sensing (DAS); (b) By geophones

DAS increased the number of weak events and also detected several additional events in the magnitude range of about −1.5 to 0.2. These extra detections were particularly concentrated in areas where the geophone array had the lowest sensitivity (Figure 5). This pattern is also visible in the size distribution shown in Figure 6 and time history shown in Figure 7. The results suggest that DAS can partly compensate for spatial gaps in geophone coverage, especially when template matching is applied.

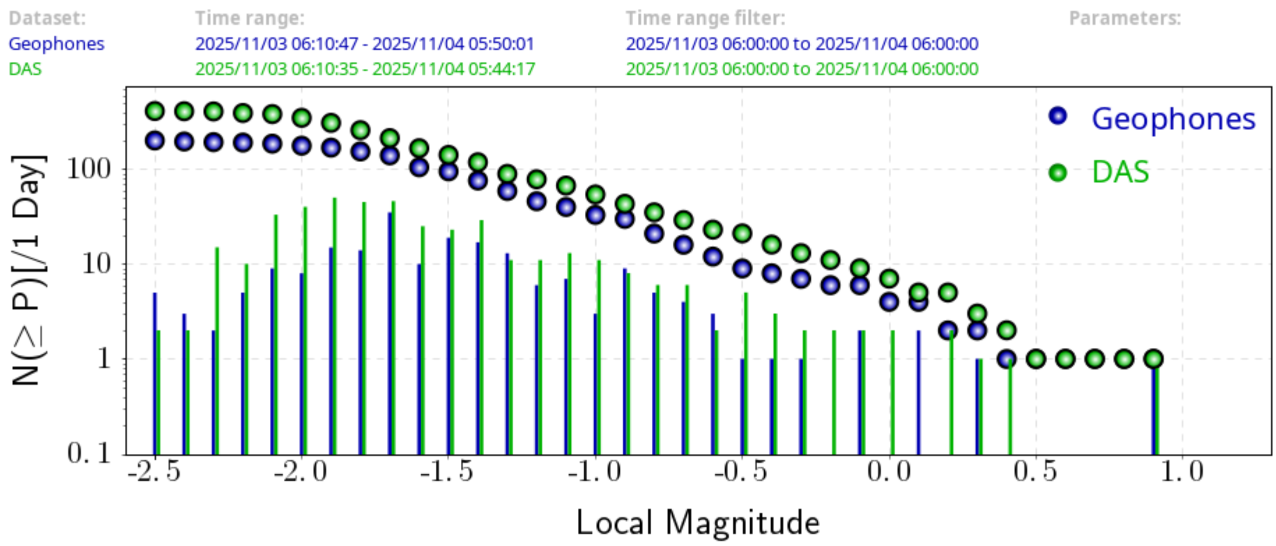

Figure 6 Comparison of event size distributions detected by distributed acoustic sensing (DAS) (green) and by geophones (blue)

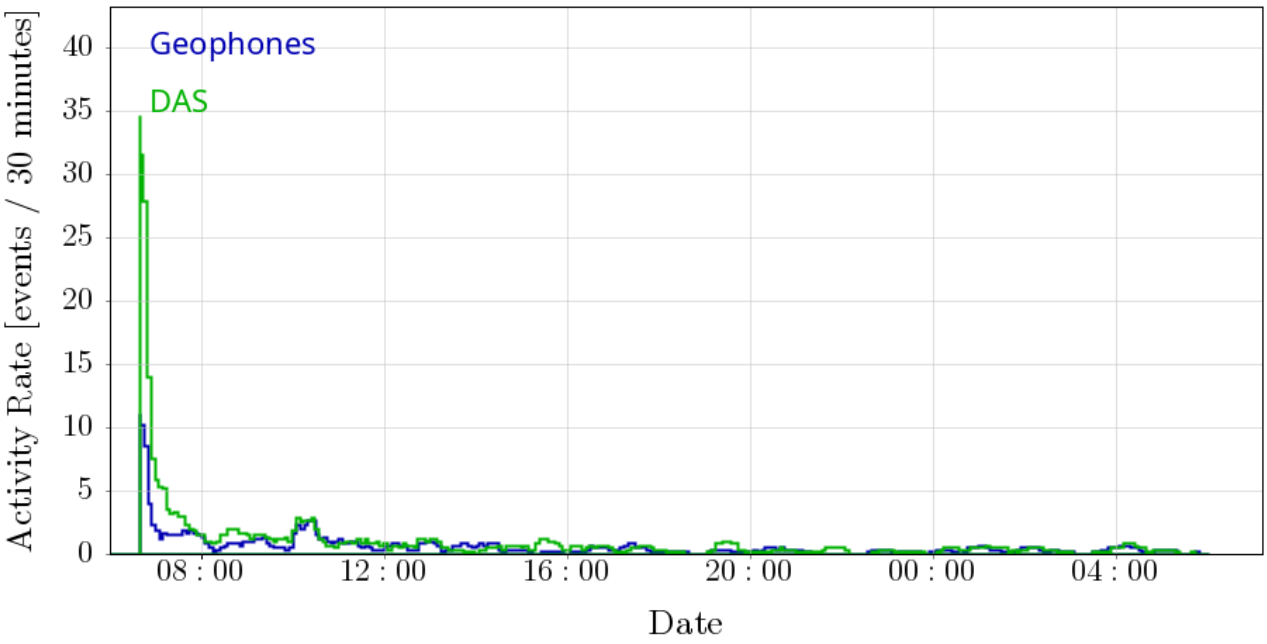

Figure 7 **Comparison of time history of seismic activity rate for events detected by distributed acoustic sensing (DAS) (green) and by geophones (blue). Most of the additionally detected events occurred within the first hour after the drawbell firing**

Figure 8 shows the relationship between event magnitude and distance from the fibre, together with the corner frequency. Most events cluster within 100–150 m of the fibre and are associated with the rock mass surrounding the drawbell firing area. No events with ML < −2.0 were detected at distances greater than 220 m from the fibre. Moreover, most events recorded further than 220 m show lower corner frequencies (generally below 100 Hz), which may be due to larger attenuation of high frequencies in the yielded zone.

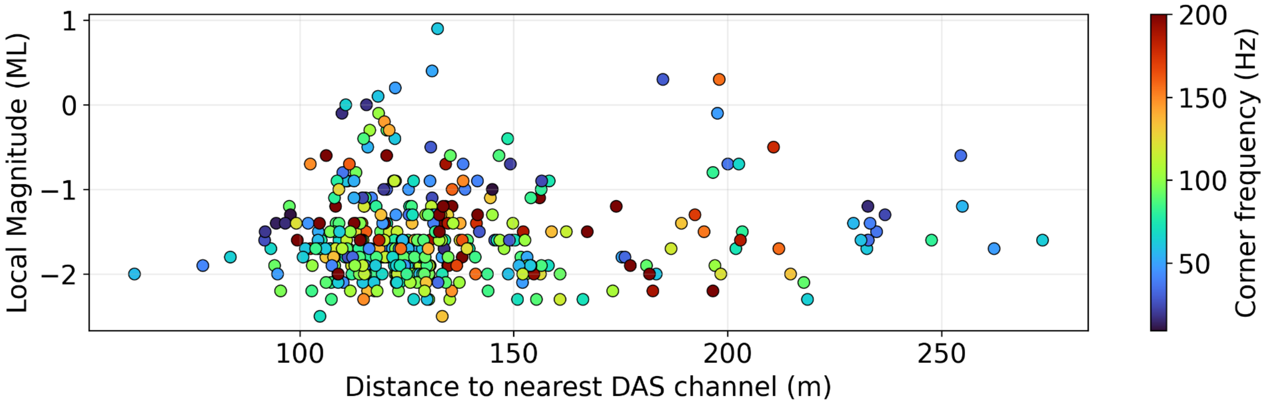

Figure 8 **Magnitude versus distance to nearest distributed acoustic sensing (DAS) channel for events detected by template matching**

6 Discussion

The dense channel spacing provided by DAS makes it well suited for detection methods such as template matching. In this study, applying template matching to a 24-hour DAS dataset approximately doubled the number of detected events compared with routine processing. The main improvement came from recovering weak repetitive post-firing events that were below the effective threshold of the standard trigger-based geophone detection algorithm. By comparing continuous data with known-event templates and combining correlation evidence across multiple DAS channels, the method improves sensitivity to coherent seismic signals without requiring any change to the acquisition set-up.

However, the method has clear limitations. Matched filtering is template dependent, so it mainly detects events that are similar to those already included in the template database. As a result, new or evolving source types may be under-represented. In addition, DAS sensitivity decreases with source–fibre distance and depends on source–fibre geometry. Spatial variations in detection density should therefore be interpreted with caution, as they may partly reflect detection capability rather than true changes in seismic response.

Another important practical issue is parameter selection. Detection thresholds must be chosen carefully to improve sensitivity without introducing too many false detections. If the thresholds are too low, the algorithm may start picking up noise or other unwanted correlation peaks. In practice, stable results require basic quality control, such as checking waveform similarity, channel consistency and the temporal separation of detections. The processing is also computationally demanding, especially for continuous DAS data and a large number of templates, and typically requires parallel execution across multiple CPUs/GPUs. For this reason, template matching is better suited to post-recording catalogue enhancement than to routine real-time monitoring.

For routine seismic monitoring, the most robust approach is a hybrid workflow. DAS template matching can significantly improve the recovery of weak near-fibre events, mainly as a post-recording processing stage. However, the conventional seismic monitoring system remains essential for reliable event location (in the case of DAS installed in a single borehole) and for detecting events outside the available template catalogue. With suitable algorithm tuning, quality control and regular template bank updates, the combined workflow can provide a basis for cave front tracking that is more complete and interpretable than either system alone.

7 Conclusion

This study demonstrates a practical template-matching workflow for underground DAS data, aimed at improving the detection of weak, repeating seismic events associated with cave establishment. By exploiting waveform similarity and stacking correlation evidence across many DAS channels, the method can extend detectability below the level achievable with standard triggers in a variable noise environment.

Applied to a 24-hour dataset surrounding a drawbell firing sequence, the workflow approximately doubled the number of detected events relative to the routine catalogue, enriching the database primarily with low-magnitude events close to the fibre route. The resulting database may improve the basis for interpreting the rock mass response to mining and can provide additional support for cave-tracking interpretation when used with appropriate quality control and awareness of DAS sensitivity limitations.

Template matching works best when similar events repeat and when the fibre is well placed relative to the target volume. The method depends on available templates and can be computationally intensive, so it is best used with carefully selected templates, basic quality control and support from conventional geophone processing. In this way, DAS-based template matching can be used as a useful extra step without changing the existing recording set-up.

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