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Enriching seismic data with noise and blasts and the importance of credibility

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Abstract

Understanding the rock mass response to mining is fundamental for both safety and productivity in seismically active mines. Seismic data provides valuable insights beyond the rock surface such as hypocentres and source parameters, enabling mining engineers to find relationships between mining operations and rock movements.

Any conclusion drawn using seismic data is directly impacted by the credibility of the estimated seismic parameters. Unfavourable sensor placements, uncertain and biased estimates in combination with missing metrics to provide proper quality assurance and quality control (QA/QC) often result in consultations with experts to interpret the parameters and to assess the correctness.

In this paper we present a robust processing solution that overcomes these challenges by utilising statistical techniques combined with self-learning capabilities. It present results from different case studies where the processing technique is applied and shows the impact of self-learning to improve the quality of the estimated parameters and in combination with easy to use tools to describe statistical uncertainty descriptions (credible regions) for intuitive QA/QC.

This paper shows that different types of data serve distinct purposes, and shows the importance of processing all triggered events, regardless of origin. Genuine seismic events are crucial for hazard assessments, while blasts and noise events generated by mining operations help evaluate and enhance the seismic system and offer valuable insights on mining activities.

Keywords: *Bayesian seismic processing, self-learning capabilities, credibility, QA/QC, data inclusion*

1 Introduction and background

Seismic events induced by mining noise or blasts, both common in mines, are troublesome for hazard assessments. Noise (e.g. orepass, scaling or drilling noise) are of small magnitudes while production blasts or development blasts are of larger magnitudes. To prevent noise events from skewing hazard assessments, various measures are implemented to filter them out at different stages of processing. However, eliminating them from the seismic catalogue, or early in the processing workflow, has problematic and negative consequences. Valuable information, and the ability to easily classify or reclassify event types by customising filters in post-processing analysis software, are lost.

1.1 Noise and blasts in hazard assessment

In a probabilistic seismic hazard assessment relying on the Gutenberg–Richter (GR) relationship (Gutenberg & Richter 1944), both the a-value and b-value affect the estimated maximum historical magnitude (M_{MAX}). The a-value determines the total seismicity rate in the volume and time of interest and the b-value describes the magnitude distribution (i.e. the proportions of small to large earthquakes). As discussed in Törnman (2021)

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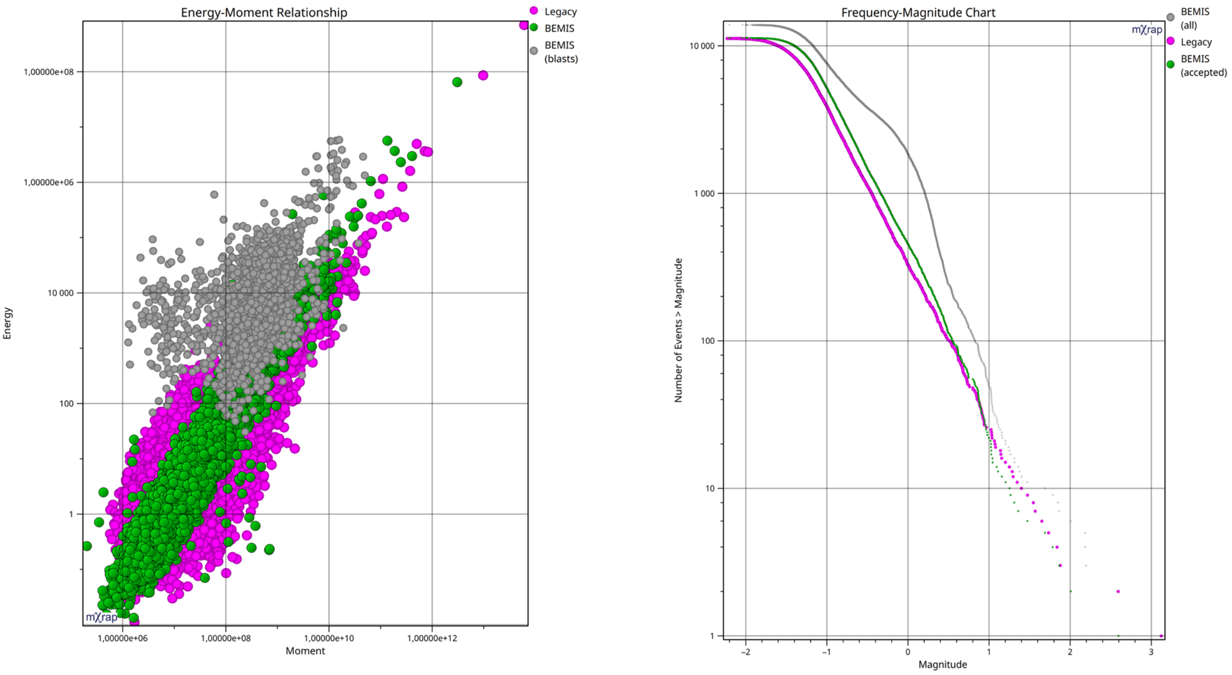
and shown in the references therein, both the a-value and b-value change with depth, and working with correct a-value and b-value is particularly important and difficult for deep mines.

The b-value can be estimated using linear regression or maximum likelihood estimation methods solving for an individual b-value or multiple b-values, both discussed in Martinsson & Jonsson (2018). Solving for an individual b-value, the resulting M_{MAX} is sensitive to misclassification of noise and blasts as events (as described in Martinsson & Jonsson 2018) and may consequently lead to over-estimating or under-estimating the seismic hazard in the mine.

Noise events (e.g. originating from ore passes, scaling or drilling) have a significantly different magnitude distribution compared to seismic events, and the b-value is significantly larger than 1.0, as shown in Törnman & Martinsson (2020). If noise events are misclassified, the frequency–magnitude relationship may contain several b-values (Martinsson & Jonnson 2018) and estimating M_{MAX} using only one b-value will underestimate the seismic hazard. Blasts, on the other hand, are usually larger than noise events, causing bumps in the GR graph as shown in Figure 1, and if included (e.g. due to misclassification), the resulting hazard may be overestimated when the GR law is applied (see Martinsson & Jonsson 2018). Wesseloo (2020) also addresses these and other difficulties along with common misconceptions in seismic hazard assessments using for example M_{MAX} and the methods of assessing it.



(a) (b)

Figure 1 Including blasts in the seismic catalogue (examples from an anonymous mine). (a) Energy moment relationship; (b) Cumulative frequency–magnitude distribution. In both (a) and (b), the pink dots are events from legacy processing. In (a) green (seismic events) and grey (blasts) are from the automatic processing routine proposed herein (seismic events with uncertainty < 17 m to match the number of accepted events from legacy processing). In (b) grey dots represent all events, including noise and blasts (with uncertainty < 17 m) from the automatic processing routine proposed herein. Figures are created in mXrap (Harris & Wesseloo 2015)

1.2 Legacy methods

The subsequent sections provide a concise overview of prevalent legacy processing and filtering methodologies. It is important to recognise that this summary encapsulates commonly applied approaches, while acknowledging the existence of exceptions.

1.2.1 Processing

In many mines, velocity models are constructed using calibration blasts with known location and/or information regarding known or modelled heterogeneities (e.g. lithologies, caved volumes, as discussed in Simser & Butler 2016).

If heterogeneities used for calibration are based on models (e.g. numerical modelling of cave shapes), any biases and inaccuracies of these underlying models will affect hypocentre locations. Other complications include the use of measured heterogeneities, such as LiDAR measurements of voids, where the measured volume underestimates the affected rock mass (Lynch et al. 2018).

While considered effective, using calibration blasts and manual inputs for calibration is resource demanding and time consuming. Also, the scope of blasting is limited to volumes near infrastructure, where blasts can be placed. Achieving good model calibration in volumes far from infrastructure requires other means.

Maintaining an up-to-date velocity model, accommodating changes in velocities as mining progresses, is a tedious and costly task.

Another important factor is the sensor system layout. For example, in areas where the arrangement is unfavourable, there will be mirroring effects or the appearance of artificial structures. Without access to location uncertainties (e.g. confidence regions or credible regions, as described by Martinsson 2013), engineers may infer the wrong conclusions. What may look like a structure may instead be an artefact of system layout. Additionally, without access to uncertainties or credible regions, engineers will have limited information available for QA/QC and it will be difficult to evaluate the effects of velocity model calibration efforts.

1.2.2 Filtering

From a computational point of view, it is resource preserving to focus processing on seismic events and to exclude or reject noise early in the workflow. However, doing so will most likely discard valuable data and hide useful information from engineers. If processed, noise offers opportunities for QA/QC, reclassification, velocity estimation, inferring velocity changes, detecting weaknesses in sensor placement, evaluating the seismic system, and hypocentre location accuracy and precision.

Another challenge related to early rejection of noise is the use of volume and/or magnitude filtering. Noise generated from known coordinates or volumes are sometimes filtered out by applying predefined volumes around the noise source, see e.g. Dineva & Boskovic (2017). However, doing so will also remove seismic events present in these volumes. For example, in LKAB's underground mines, seismic events are very common inside volumes applied for filtering (e.g. ore passes experiencing significant seismicity). Another approach to mitigate the presence of noise in the hazard assessment is to only include events with certain magnitudes (i.e. magnitude above M_{MIN}). However, as shown in Martinsson & Jonsson (2018), truncating data at a certain magnitude threshold will significantly influence estimates of b-value in terms of bias and/or precision.

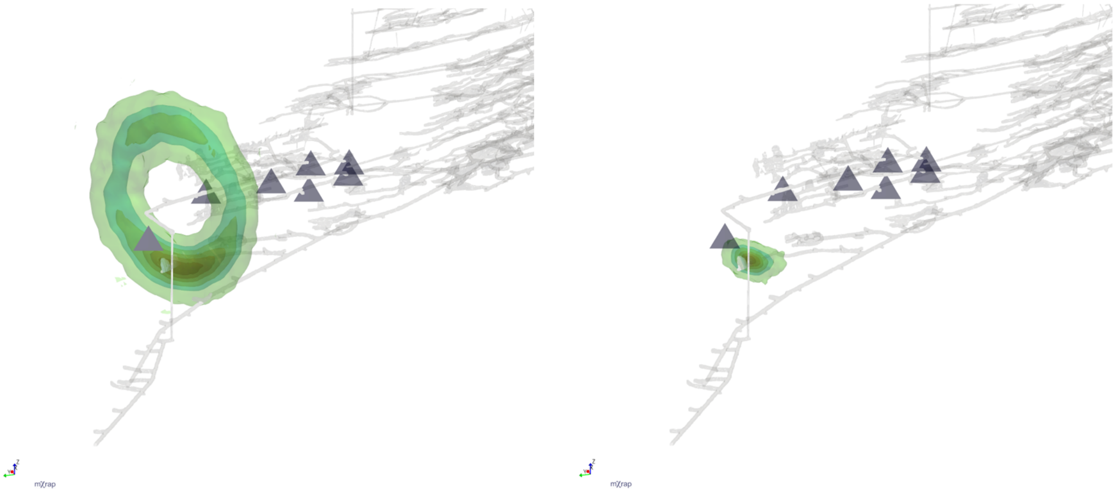
2 Method and results

This paper proposes a self-calibrating, robust processing routine where all events and their parameters and corresponding uncertainties are processed, regardless of type, and that all data (including seismograms) are made easily accessible in the user interface. Different components in the proposed routine are described in previous contributions, e.g. the Bayesian hypocentre location method is described in Martinsson (2013), the Bayesian source parameter estimation in Törnman et al. (2021), self-calibration in Törnman & Martinsson (2020) and Törnman (2021), and frequency–magnitude distribution in Martinsson & Jonsson (2018).

Optimised implementation and horizontally scalable distributed computing concepts overcome the computational intensity of this approach that may have limited its popularity in the past. With these advancements in software technology, the benefits of this routine are now broadly accessible. The main benefits of the proposed routine are explained in the following sections.

2.1 Precision and accuracy

Precision and accuracy of hypocentre location are two key aspects of overall seismic system performance. In Figure 2, hypocentre uncertainties are evaluated prior to, and after, self-calibration of velocities in an anonymous mine. These uncertainties are valuable to determine the effects of the calibration in terms of precision.



(a) (b)

Figure 2 Highlighting the effect of self-calibration in a case where the system configuration is unfavourable (examples from an anonymous mine with triggered sensors, shown as triangles, are almost distributed on a line). (a) The hypocentre distribution of an event using a homogeneous mine model. The credible region of the distribution is represented as contours of different colours; (b) The effect of the fourth iteration of self-calibration on the hypocentre distribution of the same event. Figures are created in mXrap with the BEMIS mXrap Extension software (Törnman 2023) to visualise hypocentre distributions

However, as true hypocentre locations are unknown for seismic events, they are not useful as indicators for location accuracy. For noise and blast events, however, hypocentre locations are known as they align with the infrastructure of the mine, as shown in Figure 3. Even if true blast coordinates are missing, they still provide value in detecting possible misalignment against specific features as does evaluating the hypocentre uncertainties (i.e. uncertainties should encompass or 'cover' the relevant infrastructure).

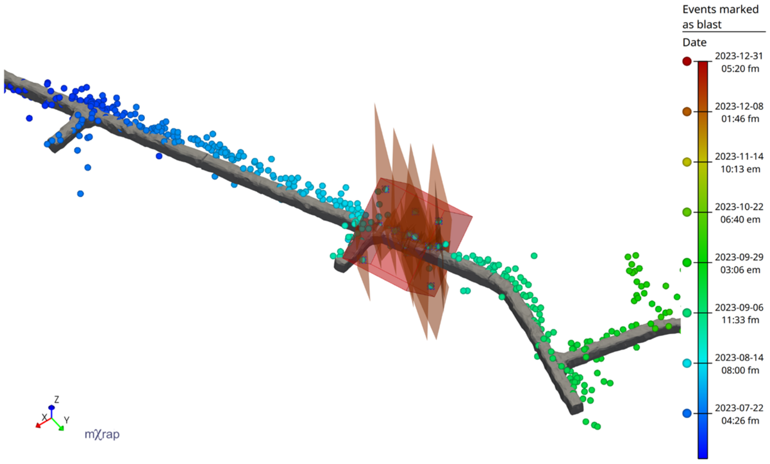


Figure 3 Events classified as blast and coloured by date, compared to infrastructure. Showing the major uncertainty plane (i.e. the plane defined by the two major principal axes of the hypocentre distribution) for events selected in the box

Therefore, these events provide valuable means of assessing accuracy of the seismic system. Processing noise and blasts and including them in the seismic catalogue provides engineers with an easy to use, intuitive, and continuously available validation of system accuracy, which helps build confidence and credibility in system performance.

While providing poor validation for system accuracy, seismic events are highly relevant when considering system precision due to the clustering nature of seismicity. High system precision will make seismic structures appear clearly in the data, as seen in Figure 4, comparing legacy processing to processing with BEMIS 2.0, the product developed from the research platform described in Törnman & Martinsson (2020) using self-calibration of the velocities.

(a) (b)

Figure 4 Comparison of self-calibration to legacy processing. (a) Shows point estimate of hypocentres of legacy processing; (b) Shows the hypocentre of accepted events estimated using BEMIS 2.0 processing after four iterations of self-calibration. Both figures are coloured by magnitude from grey to red (using the colour scale shown in Figure 7). In (b) the events are filtered with a 17 m location uncertainty to obtain a similar number of events as in the legacy processing in (a)

Conversely, low system precision will lead to a catalogue of more scattered hypocentres, potentially hiding important structures. A better understanding of structures enables engineers to manage the risks they may pose.

2.2 Classification of events

The proposed strategy means that significantly more covariates with their corresponding uncertainties are available for improved and customised classification. For example, the strategy enables development of customised classification schemes inside popular analysis tools such as mXrap (Harris & Wesseloo 2015), eliminating the need for reprocessing the entire dataset when new features are observed. It also enables filtering of data in terms of event types, parameters, and parameter uncertainties during all post-analysis. This includes, e.g. using seismic events in hazard assessments, mining noise to evaluate orepass characteristics, blasts to infer velocities or to help evaluate and enhance the seismic system and both will provide valuable insights on ongoing mining activities.

2.3 Blast and noise

Noise events originating from scaling in a tunnel or dumping material into an orepass may provide accurately located hypocentres, valuable for multiple use cases. For example, in the context of an orepass, as shown in Figure 5, noise events originate from material hitting the walls of the orepass as it falls and from hitting the floor.

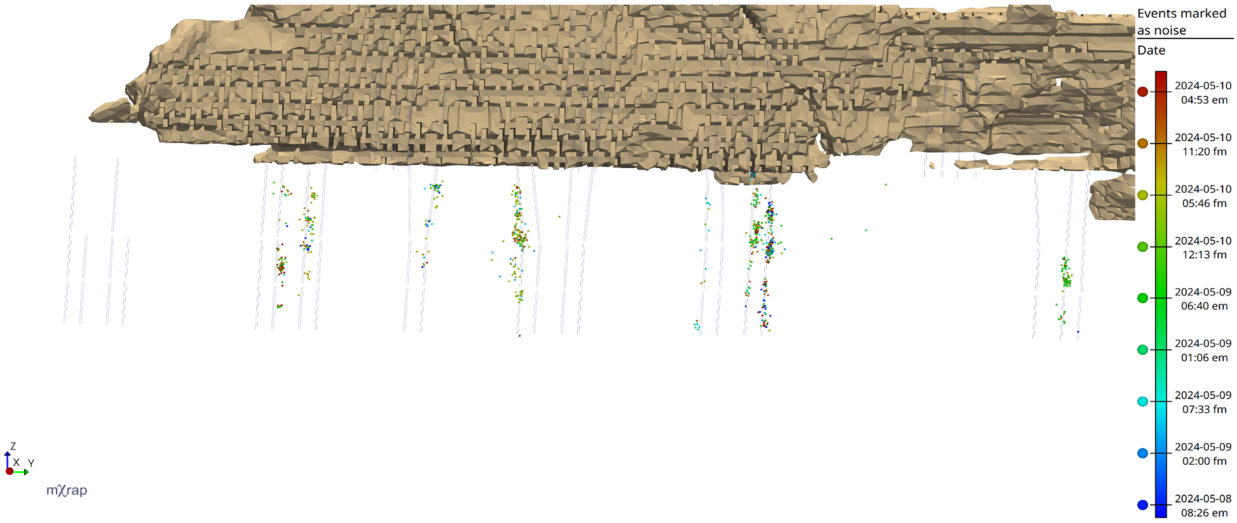
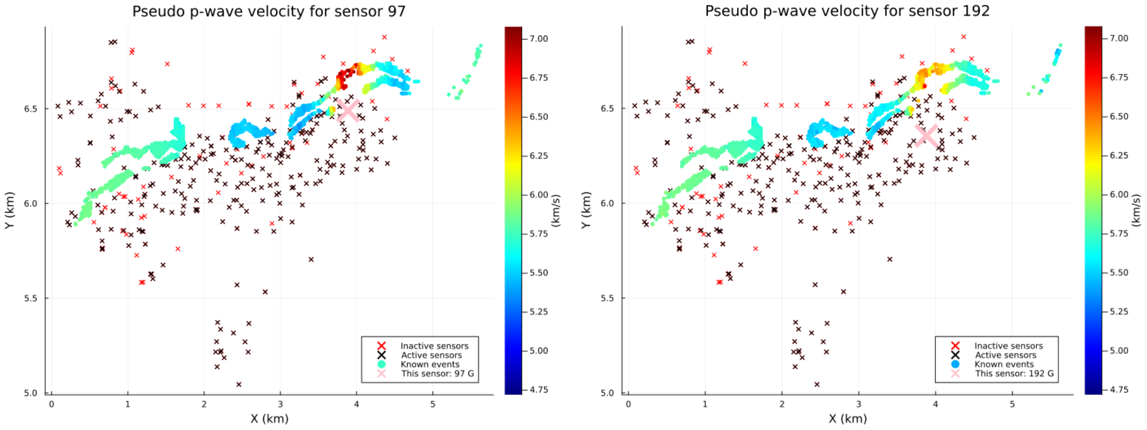


Figure 5 Example of noise showing ore passes in production

These noise events are useful for estimating the volume and the fill level of ore passes. Both these aspects of orepass state have direct implications for production (e.g. if the level is too low, the shaft will cave or the material transport system may be underutilised). Waveform analysis can be applied to detect specific characteristics which then can be combined with all the parameters and their uncertainties available in the seismic catalogue to find specific orepass events, emphasising the importance of exposing both the event catalogue and the events corresponding seismograms.

Another use case for noise and blast events in the catalogue is the near real-time view of operations they provide. With these events available in the catalogue, engineers can easily evaluate and keep track of production, as shown in Figure 3, and know which ore passes are being used by studying noise events, as shown in Figure 5.

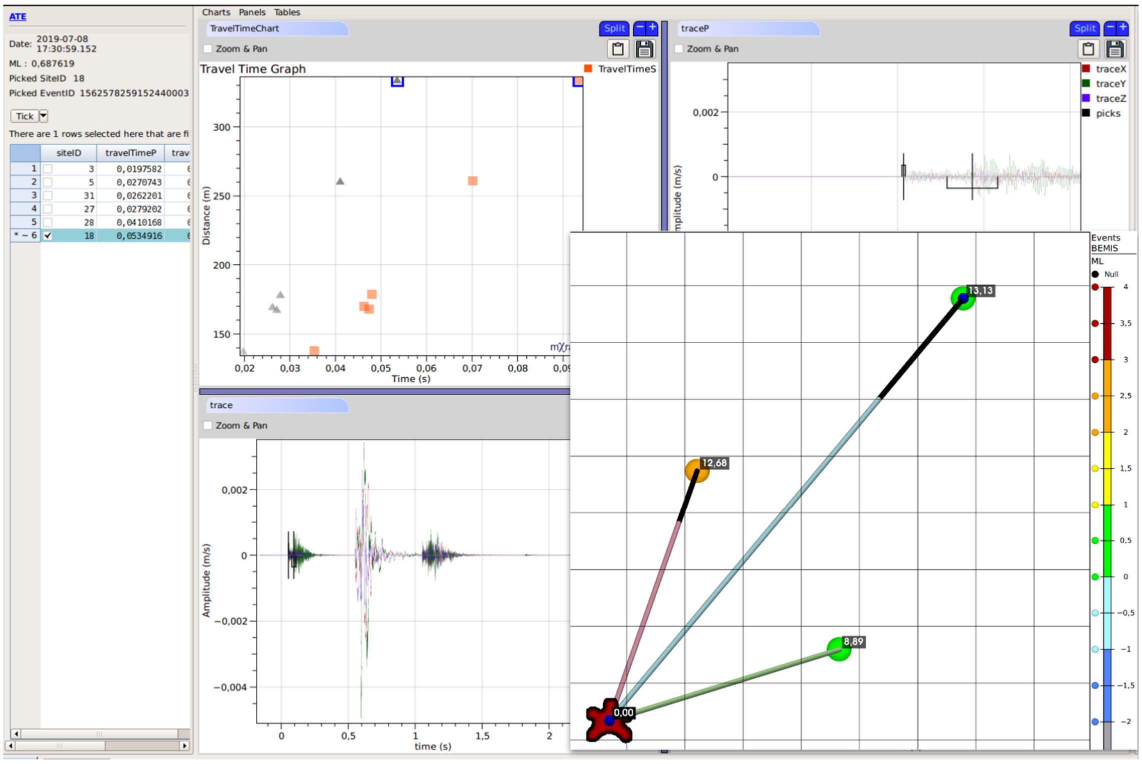
Production and development blasts can be used to study velocity anomalies and corresponding changes over time. Figure 6 shows examples of inferred velocities from production blasts by two nearby sensors, site ID 97 and 192, in the Kiruna mine, showing high velocity correlation which is useful for tomographic imaging (not covered in this paper).



(a) (b)

Figure 6 **Production blasts in Kiruna between (24 March 2023 and 15 February 2024) coloured by the pseudo P-wave velocity between sensor (pink cross) and blasts. (a) Site ID 97; (b) Site ID 192. Black and red crosses are active and inactive (i.e. no triggers were recorded in the time period) sensors, respectively.**

Keeping blast events in the catalogue, accessible from mXrap along with corresponding seismograms, also enables easy evaluation of production and development blasts in terms of sequences, timing, initiation, and superposition of waves. Figure 7 shows an example of a sequence of three waveforms in the triggered measurement window, 0.5 seconds apart. These waveforms are automatically segmented and associated into independent events providing users with daily accuracy and precision evaluation using the known coordinates of the blasts.



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4	☐	27	0,0279202	6
5	☐	28	0,0410168	6
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Figure 7 **A blast sequence recorded in a single seismogram containing three larger events. The screenshot in the background shows the waveforms, arrival time distributions and travel time chart, all in one user interface. The figure pasted in front of the screenshot (lower right) shows the hypocentre estimates for the three events, together with distance measures (in metres) with respect to blast coordinates accessible in the root folder**

2.4 Calibration

With a data-driven approach to model calibration, multiple acoustic properties of the rock mass are continuously and automatically inferred without the need for calibration blasts (described in detail in Törnman & Martinsson 2020; Törnman et al. 2021; Törnman 2021). The more data the algorithms process, the more information is used for calibration. Hypocentre uncertainty is used to assign weights for calibration. Known events (such as blasts from known coordinates) with low uncertainty are assigned high weights, and uncertain events (such as located events with estimated coordinates) are assigned low weights. Improvements from initial calibration to a self-calibrated model can be seen in Figure 2, where the hypocentre precision is improved significantly as the model describes the observations, resulting in a stronger and sharper likelihood (for example, see Martinsson 2013 for more details).

Unlike calibrations relying on calibration blast and modelled or measured heterogeneities, self-calibration updates continuously as mining progresses. High precision is obtained from seismically active regions where there are many observed data, rather than regions conducive to calibration blasts.

In situations with a low event rate and without known events, there might not be enough data to obtain detailed heterogenous calibration. This situation also suffers from slow convergence from an initial guess using homogenous models to a heterogenous model in live processing. To work around this and speed up convergence, self-calibration can be achieved by reiterating a historical batch of data to be used as an initial guess to live processing. Convergence is also affected by the sensor placement and in regions outside the sensor system, convergence is naturally slower due to larger location uncertainties.

2.5 Transparency and quality control

To instil confidence in engineers, reduce their reliance on outside experts and empower action, it is essential that all estimates are provided with quality measures and that tools provide transparency all the way down to the measurements.

This paper proposes a seismic catalogue and analysis software that includes complete data, including waveforms, arrival times (see Figure 7), locations and source parameters, with uncertainties (examples shown in Figures 2 and 8) for all estimated parameters. Easy and transparent access to this information builds confidence in the user with regards to making mining decisions.

When the geometry of the sensor network is too planar or linear, mirroring effects can be present for event locations, as shown in Figures 2a and 8. Without access to location uncertainties (confidence regions or credible regions; Martinsson 2013), engineers may infer the wrong conclusions, e.g. what may look like a structure may instead be an artefact of sensor placement, as shown in the examples in Figure 9. Additionally, without access to uncertainties or credible regions, engineers will have limited information available for QA/QC, and it will be difficult to evaluate if the calibration improved the velocity model, as described in Figure 2.

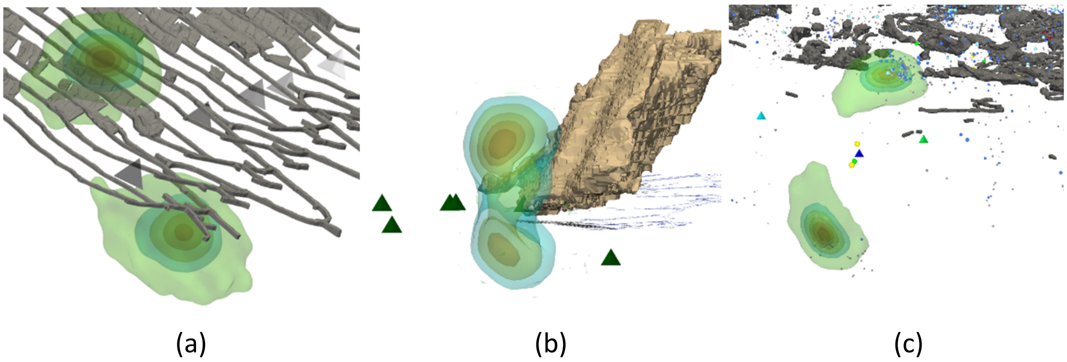
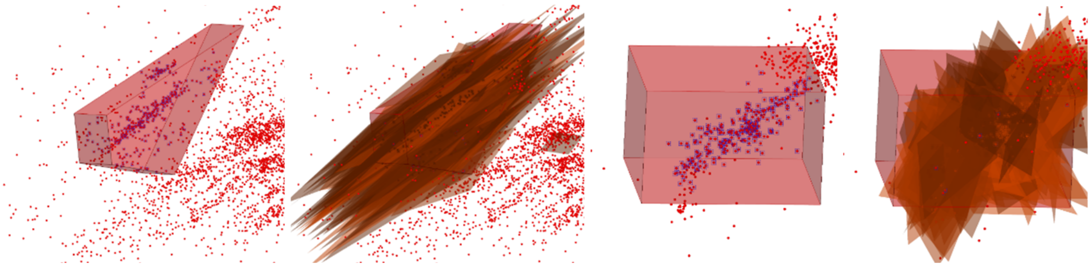

(a) (b) (c)

Figure 8 Examples of a hypocentre distribution (represented as contours of different credibility regions) showing mirroring effects for three events in three mines (a–c), caused by unfavourable sensor configurations. Triggered sensors are shown as triangles. Figures are created in mXrap with the BEMIS mXrap extension



(a) (b) (c) (d)

Figure 9 **Two examples of major uncertainty plane analysis. Figures (a) and (c) show hypocentre locations, with a box selection of events in a potential structure. Figures (b) and (d) show visualisation of the major uncertainty planes of the selected events in (a) and (c), respectively, where (b) indicates a system artefact and (d) indicates a genuine structure. The major uncertainty plane is the plane defined by the two major principal axes of the hypocentre distribution**

2.6 Data-driven innovation

Providing open access to complete data for the end users in every step along the processing allows for innovation. This increased transparency allows review of all aspects of processing results. In the BEMIS processing platform, access is provided through open APIs where consultants, engineers and scientists can easily access and review (avoiding self-audit of results) data using basic and broadly available tools, such as a web browser or mXrap.

Additionally, easy and open access to complete data allows for multi-vendor ecosystems, where best-in-breed actors can collaborate flexibly and in healthy competition, reducing lock-in effects, driving innovation and keeping costs in check.

3 Conclusion

This paper introduces a fully automatic robust processing routine for seismic data, aiming to process all events and their parameters regardless of type, including uncertainties, and make data easily accessible in the user interface. It draws on various methodologies outlined in previous works, such as Bayesian hypocentre location, Bayesian source parameter estimation and self-learning capabilities.

The software addresses computational intensity through optimised implementation and horizontally scalable distributed computing, making its benefits more accessible. The key advantages are:

- Precision and accuracy: The routine enhances both precision and accuracy of hypocentre location, crucial for seismic system performance. It distinguishes between seismic events, noise and blasts, leveraging the latter for accurate system validation.
- Classification of events: More covariates and uncertainties enable improved event classification, aiding in customised analysis without requiring entire dataset reprocessing.
- Blast and noise: Noise events, like those from tunnel scaling or orepass mucking, offer insights into operational aspects such as orepass volume and fill level, aiding in production management. Blast events provide real-time operational views and facilitate velocity anomaly studies.
- Calibration: Continuous, data-driven calibration updates acoustic properties of the rock mass automatically, with a focus on self-calibration that adapts as mining progresses. This ensures accuracy even in low-event-rate scenarios and regions outside sensor systems.
- Transparency and quality control: Providing quality measures and transparent data access down to the measurement level instils confidence in users. Access to credible regions and uncertainties aids in avoiding misinterpretations due to sensor placement or data biases and plays a crucial role in mapping for damages.

- Data-driven innovation: Keeping complete data in the seismic catalogue, ranging from measured waveforms to processed hypocentres and source parameters for all types of events, is foundational for data-driven innovation initiatives. With such a rich data platform, multi-disciplinary scientists and engineers can collaborate using modern tools, including Artificial Intelligence and machine learning.

Overall, the paper emphasises accessibility, precision, and adaptability in seismic data processing, offering practical benefits for mining operations and system performance evaluation.

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