Statistical and clustering analysis of microseismicity from a Saskatchewan potash mine

Mohammadamin Sedghizadeh [1], Robert Shcherbakov [1,2] and Matthew van den Berghe [3]

[1]Department of Earth Sciences, University of Western Ontario, Canada.

[2]Department of Physics and Astronomy, University of Western Ontario, Canada.

[3]Nutrien Ltd., Canada.

Summary

Microseismicity is expected in potash mining due to the associated rock-mass response. This phenomenon is known, but not fully understood. To assess the safety and efficiency of mining operations, producers must quantitatively discern between normal and abnormal seismic activity. In this work, statistical aspects and clustering of microseismicity from a Saskatchewan, Canada potash mine, are analyzed and quantified. Specifically, the frequency-magnitude statistics display a rich behaviour that deviates from the standard Gutenberg-Richter scaling for small magnitudes. To model the magnitude distribution, we consider two additional models, i.e., the tapered Pareto distribution and a mixture of the tapered Pareto and Pareto distributions to fit the bi-modal catalogue data. To study the clustering aspects of the observed microseismicity, the nearest-neighbour distance (NND) method is applied. This allowed the identification of potential cluster characteristics in time, space, and magnitude domains. The implemented modelling approaches and obtained results will be used to further advance strategies and protocols for the safe and efficient operation of potash mines.

Methods

In this study, we focused on the statistical analysis of microseismicity associated with mining operations in a Saskatchewan, Canada potash mine. Several statistical models have been considered to investigate various aspects of mining seismicity. This included the estimation of the magnitude of the completeness of the analyzed catalogue using several catalogue-based methods (Cao & Gao, 2002; Woessner & Wiemer, 2005). The frequency-magnitude statistics were modelled by considering several parametric distributions to establish an appropriate model. This includes the standard exponential distribution (Vere-Jones, 2010), the upper-truncated and tapered Pareto distributions (Kagan, 2002), and the mixture of the above distributions. The maximum likelihood method was utilized to estimate the model parameters. Classification of the mining seismicity in terms of the mode of triggering and possible rheological regimes was performed using the NND clustering method (Baiesi and Paczuski, 2004; Zaliapin et al., 2008; Zaliapin & Ben-Zion, 2013).

Mining seismicity data

In order to analyze the seismicity of a Nutrien potash mine, a manually reviewed microseismic catalogue was used. The spatial distribution of events above magnitude $m \geq -2.97$ is shown in Figure 1. The catalogue spans the time interval between 01/05/2019 and 07/09/2021. The original catalogue contained 11,633 events. For the analysis, it was reduced to 9,268 events by manually removing the events associated with the network calibrating surface shots that were performed between 02/12/2021 and 02/19/2021.

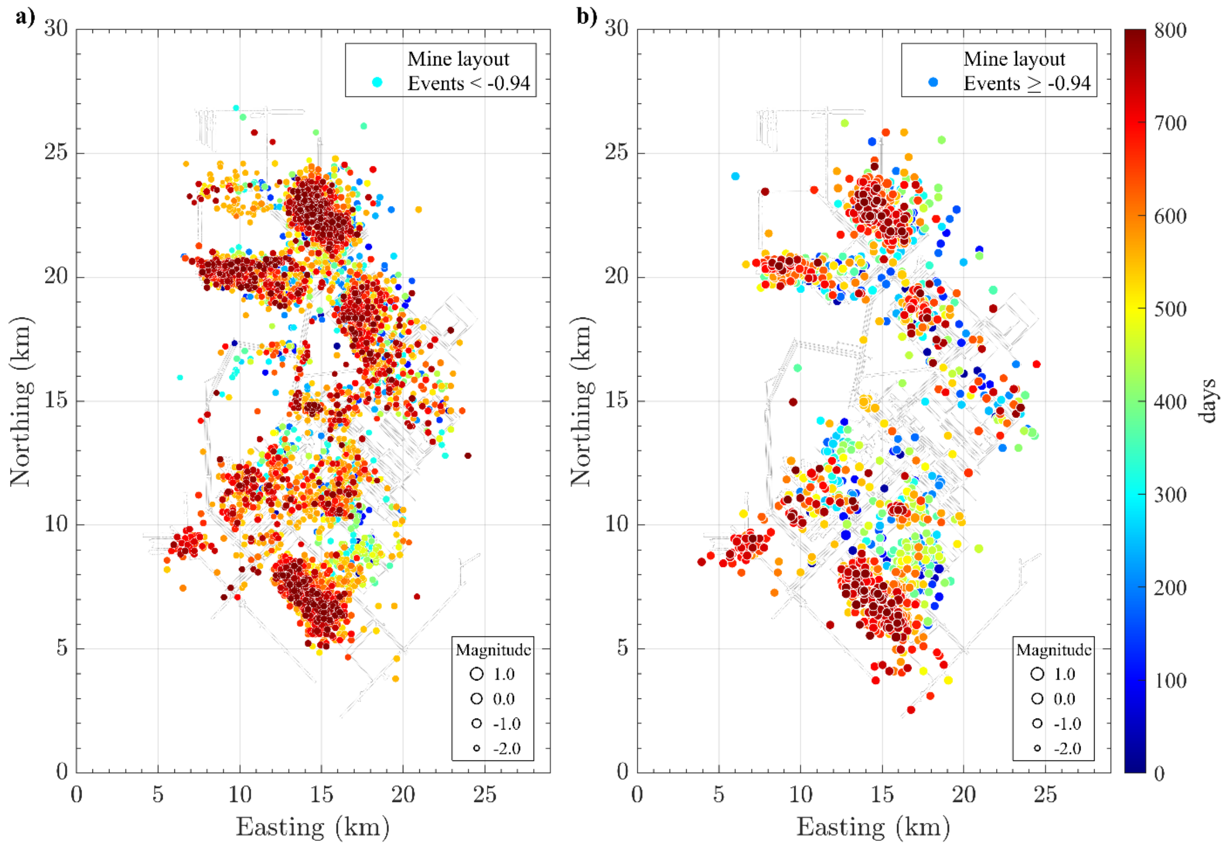

Figure 1 The plot of the epicentres of microseismicity in a potash mine in Saskatchewan, Canada. The events were recorded from May 1, 2019, to July 9, 2021. The coloured solid circles represent events with magnitudes a) below $m <$ -0.94, and b) above $m \geq$ -0.94. Different colours indicate the time of the occurrence of events and are given by the colour bar with the corresponding times in days starting from May 1, 2019. The light gray lines illustrate the layout of the mine.

Results

To ensure a comprehensive analysis, the magnitude of the completeness was derived using several catalogue-based methods. These included the method of maximum curvature (MAXC) (Wiemer & Wyss, 2000), the G-R b-value stability (MBS) method (Cao & Gao, 2002; Woessner & Wiemer, 2005), and the method based on the goodness-of-fit test (GFT) (Wiemer & Wyss, 2000).

The frequency-magnitude statistics of the microseismicity in the mine were modelled using the exponential distribution, by magnitude binning of 0.01. The magnitude of completeness, m_c, was used as the lower magnitude cutoff, m_{min}. This was done for several possible values of m_c that were estimated using MAXC, MBS, and GFT methods. The obtained completeness magnitude m_c = -0.94 from the MBS approach was considered for further analysis.

To investigate any possible bi-modality in the frequency-magnitude statistics the event magnitudes were modelled by two additional distributions. Specifically, we considered the tapered Pareto distribution as well as the mixture of the tapered Pareto and Pareto distributions. Using the lower magnitude cutoff $m_c = -0.94$ the fits of the frequency-magnitude distribution are given in Figure 2.

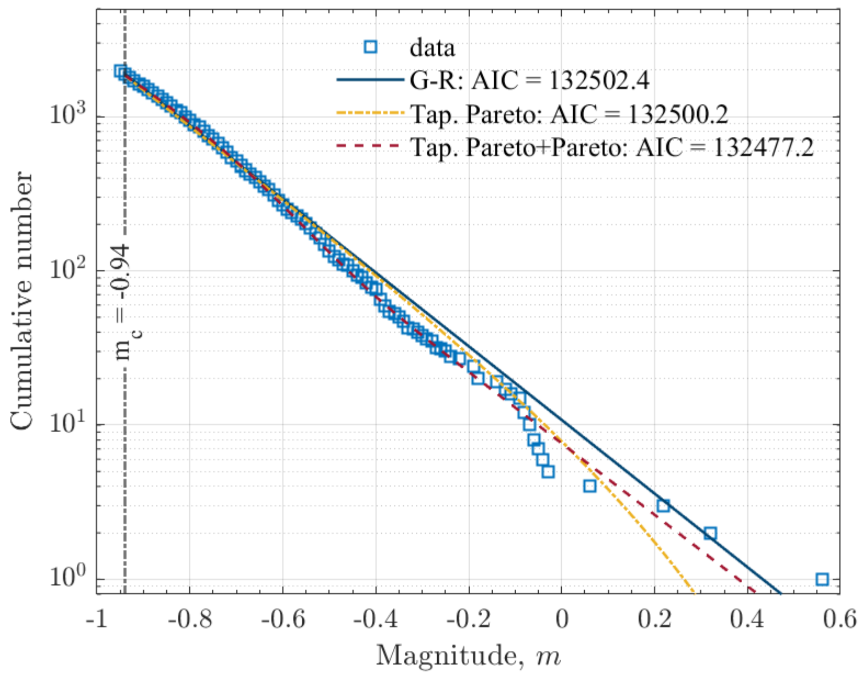

Figure 2 The frequency-magnitude statistics for the mining-induced seismicity. The blue open squares represent the cumulative number of events. The dark blue line is the fit of the G-R scaling. The dash-doted line is the fit of the tapered Pareto distribution. The dashed line is the fit of the mixture of the tapered Pareto and Pareto distributions.

The clustering of induced mining seismicity was analyzed using the NND method. In this analysis, we used b = 2.39, d_f = 1.6, and considered the epicentral distances between events with magnitudes above m_{min} = -0.94 when computing the rescaled times and distances. The obtained distributions of the rescaled distances R and times T as well as the nearest-neighbour proximity η are given in Figure 3. The multi-modality of the distribution of η was studied by fitting the Gaussian mixture model (GMM). The fit of the two-component GMM is given in Figure 3.

Within the NND analysis, seismic family trees that form the clustered events can be subdivided into three main types: swarm-like, burst-type, or aftershocks (Zaliapin & Ben-Zion, 2013, 2016). The swarm-like families are those chains of seismic events without branches. The burst-type families are those that have only one parent event and many children. The aftershock-type families are the combination of both mentioned types and contain first or higher-order triggered events. By applying this classification to the mining microseismicity we were able to identify 52 families (groups of microseismic events) that had more than 2 nodes. Using the criterion based on the value of the inverted branching number, B_I, (B_I = 1 swarm-type, B_I > 0.5 aftershock-type, and $B_I \leq 0.5$ burst-type), from these 52 seismic family trees, 18 families had swarm-type, 8 family trees had aftershock-type, and the remaining had burst-type characteristics. This indicates that the "burst-type" of activity dominates the clustering. Specifically, the "burst-type" sequences have small depths and are dominated by first-generation offspring of mainshocks and have additional spatiotemporal and internal topological properties consistent with highly brittle behaviour. It should be mentioned from these 52 family trees, 17 families had a foreshock sequence, and in the other 35 families, the root event was the largest event in the family tree.

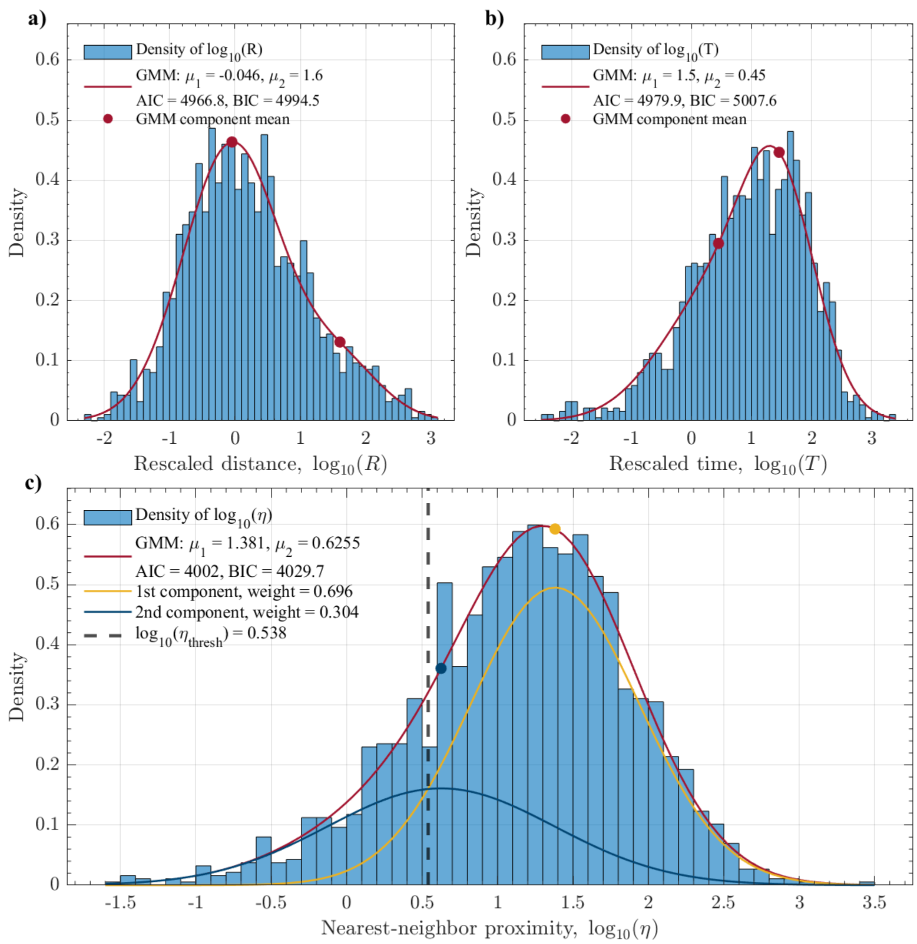

Figure 3 The distributions of the a) rescaled distances R, b) rescaled times T, and c) nearest-neighbour proximity η for all events above magnitude $m \geq -0.94$. The dark red curves are the fits of the two-component Gaussian mixture model to each distribution. The individual components are shown in c) as yellow and blue solid curves with the corresponding means and weights given in the legend. The threshold $\log_{10}(\eta_{thresh}) = 0.538$ was estimated from the intersection of the two components and is shown as a vertical dashed line.

Conclusions

In this work, several statistical methods were applied to investigate the nature of microseismicity in a Saskatchewan potash mine. Specifically, the modelling of the frequency-magnitude statistics was performed by fitting several models: the left-truncated exponential distribution (or equivalently G-R scaling), the tapered Pareto distribution, and their mixtures. The magnitude of completeness was estimated using several methods and we used $m_c = -0.94$ for the analysis. The results of the clustering analysis of microseismicity indicate that the majority of events can be treated as independent background events mostly driven by underground mining operations. However, there is some clustering of seismicity and the formation of limited aftershock sequences. This clustering is predominantly of "burst-type" in the terminology adopted in the NND analysis.

From the analysis performed in this work, we can draw several specific conclusions concerning the observed mining microseismicity. The frequency-magnitude distribution of seismicity exhibits a relatively high *b*-value (b = 2.39±0.15) indicating that the seismic events are distributed in a rather narrow magnitude range above the completeness threshold $m \geq -0.94$. The largest observed event during the study period had a magnitude of 0.56. The interevent triggering is also suppressed and does not show any significant cascade-like propagation of seismicity. This suggests that the probability of having even larger events is very low and does not constitute a significant hazard for the safe operation of the mine.

Acknowledgements

We acknowledge Nutrien Ltd.'s permission to use the mining microseismic catalogue, generated through a collaborative effort of Nutrien Ltd and the Nanometrics Seismic Monitoring solutions Teams. This research work has been supported by the Accelerate grant from Mitacs and International Minerals Innovation Institute to study mining microseismicity.

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