Deep Mining 2024 – P Andrieux & D Cumming-Potvin (eds)
© 2024 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-9-6
doi:10.36487/ACG_repo/2465_68

The role of geological features in mine seismicity: Kanowna Belle case study

Afranio L Moreira de Oliveira [a,b,*], Roohollah Shirani Faradonbeh [b], Izak G Morkel [c], Roo Talebi [d]

[a] *Northern Star Resources Limited, Australia*

[b] *Curtin University, Australia*

[c] *IGM Geotechnical, Australia*

[d] *Gold Fields Australia, Australia*

Abstract

Accurate assessment of seismic source mechanisms is important in seismic monitoring in underground mines. Complexities in seismic source identification, particularly inconsistencies in datasets, may significantly impact the interpretation and accuracy of seismic data analysis. To address this issue, a method for identifying seismic source mechanisms based on the Hudson's Diagram analysis is presented, in which seismic events are classified as blast, slip-type, or crush-type events. Furthermore, in this study, nodal planes and photogrammetry were used to delineate potential slip-planes, which was discovered to be a valuable alternative to map structures where visual mapping is impossible due to the use of shotcrete in-cycle. Finally, the relationship between geological features and seismicity was investigated at the Kanowna Belle mine, where seismicity is described as primarily influenced by geological features. The findings of this study contribute to a better understanding of lithological contact seismic behaviour and the comprehension of seismic monitoring to address the associated seismic hazard. Moreover, it provides tools for early ground support design adjustments and ensures a safe working environment, increasing mine efficiency.

Keywords: *mine seismicity, moment tensor inversion, source mechanism, geology*

1 Introduction

Underground mining activities invariably disrupt the in situ rock stress, often leading to its concentration around excavation boundaries and unmined pillars commonly used for additional ground support (Heal 2010; Potvin & Wesseloo 2013). Such mining operations can induce elastic and inelastic deformations in nearby rock formations. Reversible elastic deformation involves accumulating strain energy that may be released progressively or suddenly during the onset of inelastic, irreversible deformations, such as fractures and slippage, generating seismic waves (Mendecki 1996).

Mine operations frequently generate seismic waves from the interaction between geological structures, faults, lithological contacts, and shears within regional and local stress fields (Snelling et al. 2013). The release of seismic energy occurs when frictional instability occurs on a geological site or when rocks are disturbed, often forming new features (Urbancic & Trifu 2000).

Rockbursts, characterised by the sudden (dynamic) and extreme release of stored strain energy within rock masses, pose significant hazards to mining operations, potentially resulting in fatalities, equipment damage, and local closures (Faradonbeh et al. 2020a). These events typically occur when induced stress exceeds the in situ rock mass strength, leading to rock collapse (Ortlepp 1997). Rockbursts are commonly attributed to seismicity resulting from mining activities and energy discharge associated with geological structures, making them one of the most severe hazards in mining operations (Gibowicz & Kijko 2013; Li et al. 2014).

---

[*] Corresponding author. Email address: aoliveira@nsrltd.com

The likelihood of rockbursts increases with mining depth, particularly in high-stress zones such as faults, folds, and residual pillar areas (Faradonbeh et al. 2020b; Li et al. 2014).

This study aims to identify geological structures based on mine seismicity and geotechnical databases available at Kanowna Belle mine.

2 Geological investigation

2.1 Location, geological setting, and mining method

The Kanowna Belle gold mine, owned by Northern Star Resources Ltd, is situated in the Yilgarn Craton, 18 km northeast of Kalgoorlie and 2 km west of the historical gold mining centre of Kanowna, Western Australia (Varden & Esterhuizen 2012).

The deposit is hosted within sedimentary volcaniclastic and conglomeratic rocks. These rocks are divided into hanging wall and footwall stages by a large, steeply southeast-dipping zone of structural disruption. This structural configuration results from at least three chronologically separate deformation stages: the Fitzroy Mylonite, the Fitzroy Shear Zone, and the Fitzroy Fault. These deformation phases exhibit visible structural overprinting relations. Notably, this structure has defined the emplacement of the Kanowna Belle porphyry, which contains at least 70% of known mineralisation (Sugiono et al. 2021).

Various other significant structures have been identified that influence ground conditions. These include the porphyry zone (PMT), contacts between felsic intrusive and porphyries, the hanging wall shear and the footwall shear (Varden et al. 2008). Figure 1 is a detailed representation of the local geology map, illustrating different lithological groups.

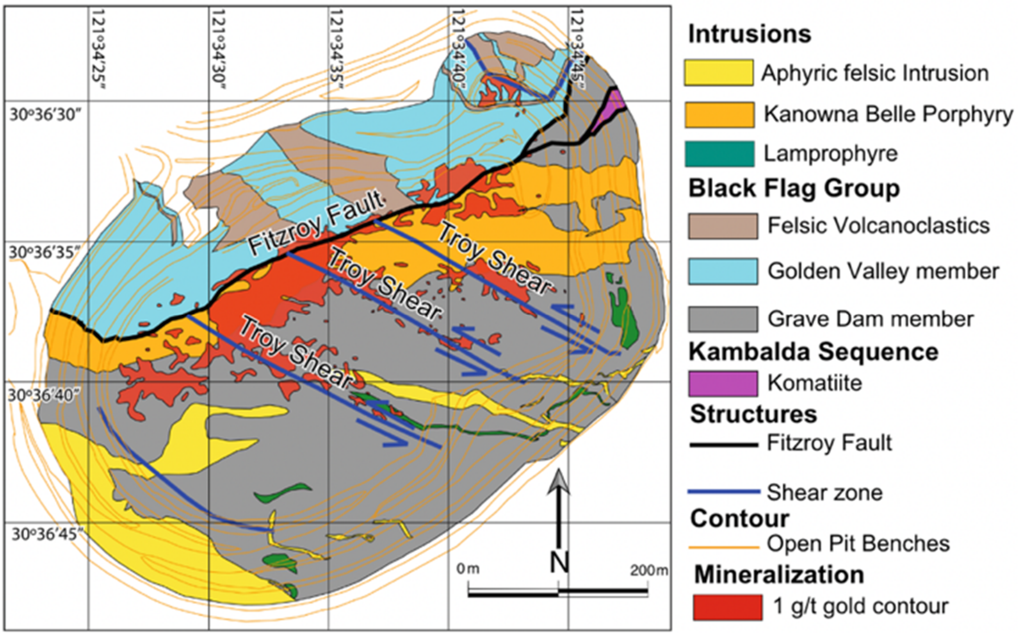


Figure 1 Kanowna Belle geology map (Sugiono et al. 2021)

The mine has been divided into distinct mining blocks, each at different extraction stages. A block is thoroughly mined, B block is partially mined, C block is almost entirely mined, D block is actively mined, and E block is in both development and production phases. The mining method employed is long-hole open-stoping mining with 30 m sub-levels. Operations are concurrently conducted in multiple headings at various depths (Varden & Esterhuizen 2012).

The mine is divided into seven domains based on lithology, with conglomerates, porphyry, and felsic units comprising the primary lithologies. The Fitzroy Fault is characterised as a gouge zone ranging in width from 1–100 cm and plays a significant role. It is 2.5–14 m from the delineated contact known as the hanging wall

Shear. The Footwall Shear comprises a sequence of spread structures with minimal effect on stability and is fully defined. The Fitzroy Fault intersects five felsic units traversing the footwall domains: the Velvet Footwall Fault (VFT), Moore, Larkin, Isabella, and Wilson units (Varden et al. 2008).

2.2 Local structures and rock mass discontinuities

Structures that intersect the excavations or are nearby, significantly influence the stability of underground excavations. The primary discontinuities that exert localised effects on excavation stability include:

- Bedding: This feature is subparallel to Felsic Units (approximately 65°/240°) and is present in all major lithologies at Kanowna Belle (excluding Porphyries).
- Various joint settings: These settings vary throughout the mine.
- Faults and shears: These can be subparallel or oblique to the bedding planes.

Interpreting routine development mapping, drill holes, and geotechnical inspections facilitates the ongoing updating of the mine's structural model.

2.3 Seismic system and underground monitoring

The Institute of Mine Seismicity (IMS) seismic system was installed in May 2000 in response to increasing levels of seismicity during the development of C block. Geological structures control the occurrence of significant seismic events. The mine is equipped with an extensive seismic sensor array that operates 24 hours a day. Figure 2 is a schematic view of the sensor positions for Kanowna Belle mine. IMS is responsible for processing seismic data in real-time and providing daily, weekly, and monthly reports.

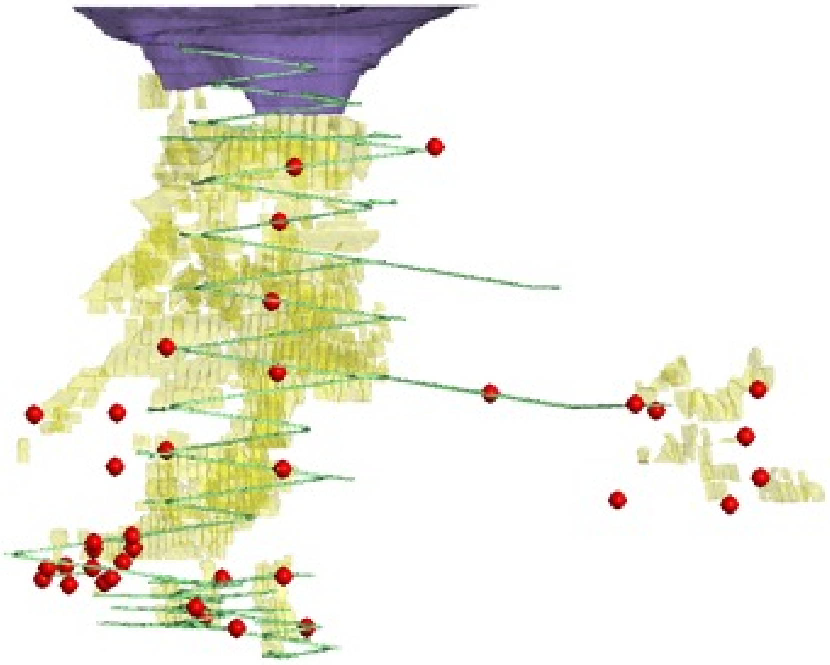


Figure 2 Current seismic sensor array at Kanowna Belle, looking south

The geotechnical department has devised control strategies to mitigate risks to personnel and production; encompassing analysis, design, support, and exclusion zones. Proper implementation of these strategies aims to achieve several objectives:

- reducing seismic-related damage to manageable levels
- minimising potential safety implications associated with seismic damage

- optimising or minimising costly rehabilitation work related to seismic damage
- mitigating unplanned delays or interruptions to the production cycle.

3 Identification of seismic source parameter for the seismic source mechanism at the Kanowna Belle mine

Previous research on the failure mechanism at Kanowna Belle has characterised it as a fault slip (Varden & Esterhuizen 2012), determined using the Es:Ep Energy ratio method (Dahm & Krüger 2014; Heal 2010; Hudyma 2008; Varden & Esterhuizen 2012; Vavryčuk 2015). This method suggests a shear mechanism for the existing structures. However, a recent study by Morkel et al. (2019) has investigated and quantified the consistency and applicability of this parameter. The study found that inconsistencies in the dataset could significantly impact the interpretation and accuracy of data analysis. Therefore, it is cautioned against employing this parameter as a source mechanism indicator when its reliability is questioned. It has become increasingly easier and economical to do a moment tensor inversion (MTI) for most seismic events, which is much more useful and accurate than the Es:Ep parameter.

The seismic data were analysed using the software mXrap from the Australian Centre of Geomechanics (Harris & Wesseloo 2015) and the IMS Vantage package from the Institute of Mine Seismology.

To ensure the accuracy of the seismic source parameters, the process outlined in Figure 3 is applied. By ensuring the process is robust and detailed, many of the challenges involved with source parameter quality is circumvented.

Figure 3 Flow chart to determine the seismic parameters for the seismic source mechanism at the Kanowna Belle gold mine

Seismic data collection at Kanowna Belle began in May 2000 with the deployment of the IMS system, marking the start of continuous recording within the mine. Over the years, this system has accumulated a vast dataset, logging more than 311,000 seismic events; encompassing blasts, heavy machinery operations, and orepass noise.

A magnitude filter of ML > 0.0 was used as only significant seismic events were considered. Given the intricate nature of seismic events, particularly within mining contexts, not all seismic source mechanisms remain readily discernible. Only those events with moment tensor solution provided by IMS were considered; of the 1,812 significant seismic events 238 had MTI solutions.

The method uses blast locations recorded during seismic sensor calibration to determine the velocities of geophones for the area in question. This ensures accurate seismic source parameters and event locations. Furthermore, the MTI for many of the large events are provided by the Institute of Mine Seismology for Kanowna Belle mine. There are, however, historic events with source parameters calculated with only a few seismic sensors included in the database. However, the source mechanisms of seismic events have become more reliable in recent years as the number of seismic sensors has increased.

When scrutinising seismic events using moment tensors, they are typically decomposed into two primary components. Firstly, there is the isotropic component, indicating any volume change, whether expansion (positive values) or contraction (negative values) (Dahm & Krüger 2014). Secondly, the deviatoric component reflects the displacement along faults (Vavryčuk 2015). To gain deeper insights into the relative proportions of shear and normal displacement, the deviatoric component can be further subdivided into a double couple (DC) component and a compensated linear vector dipole component (Vavryčuk 2015).

For this purpose, Hudson introduced a diamond-shaped source type diagram in 1989 (Hudson et al. 1989), as illustrated in Figure 4. In this diagram, the pure DC component resides in the origin, representing a fault slip mechanism. Pure explosions and isotropic implosions are situated along the vertical axis of the diagram, denoted by +ISO and −ISO, respectively (Dahm & Krüger 2014). A seismic source demonstrating shear faulting exhibits a prominent DC component (Vavryčuk 2015).

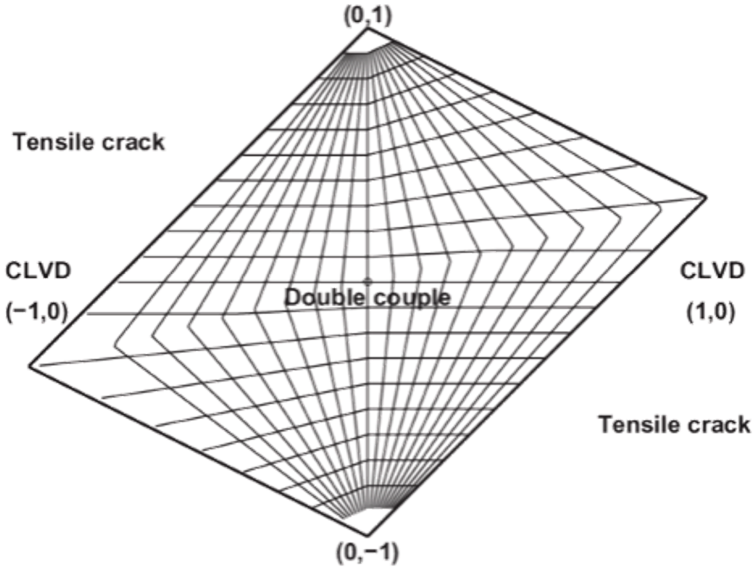


Figure 4 Hudson's skewed diamond source type diagram (Hudson et al. 1989)

Malovichko & Rigby (2022) have suggested that the Hudson's Diagram (Figure 5), can be interpreted to have three main mechanism types; blasts, slip-type and crush-type events. The red section in Figure 5 correspond to the top vertical axis, indicating +ISO, which signifies a zone of high isotropic explosion, often associated with blasts. A crush-type event (blue area) typically displays roughly equal proportions of isotropic and compensated linear vector dipole (CLVD) components, with minimal DC contribution, appearing in the lower blue area of the diagram. Conversely, a slip-type event exhibits stronger DC components relative to CLVD and ISO, locating it within the middle green area.

For Kanowna Belle the events investigated constitutes 65% slip-type and 35% crush-type events, suggesting a direct influence of geological features on seismicity. The statistics is based on where the events plot on the Hudson diagram in Figure 5.

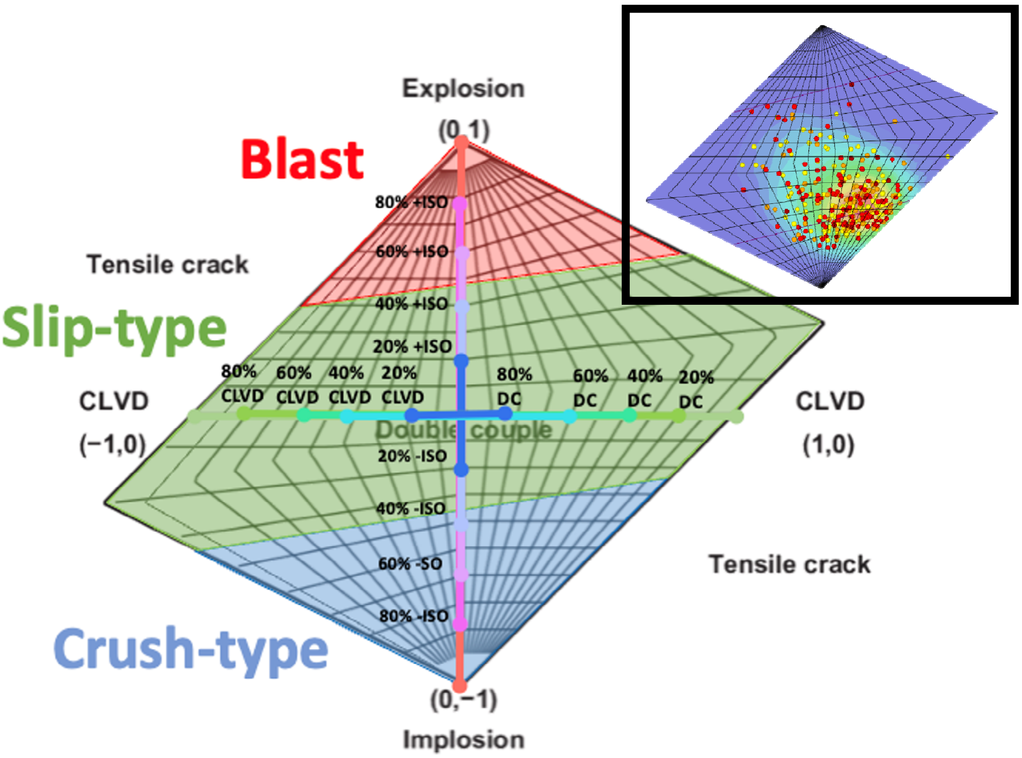


Figure 5 Hudson's skewed diamond diagram interpretation (Malovichko & Rigby 2022). Figure insert: Kanowna Belle mine Hudson diagram plot for events (ML > 0.0)

Previous research classified the seismic behaviour at Kanowna Belle as fault slip, attributing seismicity primarily to structural factors based on the S:P Energy Ratio (Varden & Esterhuizen 2012). However, a recent study investigated the consistency and applicability of using the S:P Energy ratio to interpret seismic events. It revealed that inconsistencies in datasets could significantly impact interpretation and data analysis accuracy (Morkel et al. 2019). Therefore, to ensure the accuracy of the study, only events with an MTI were considered, unlike the Varden & Esterhuizen (2012) study.

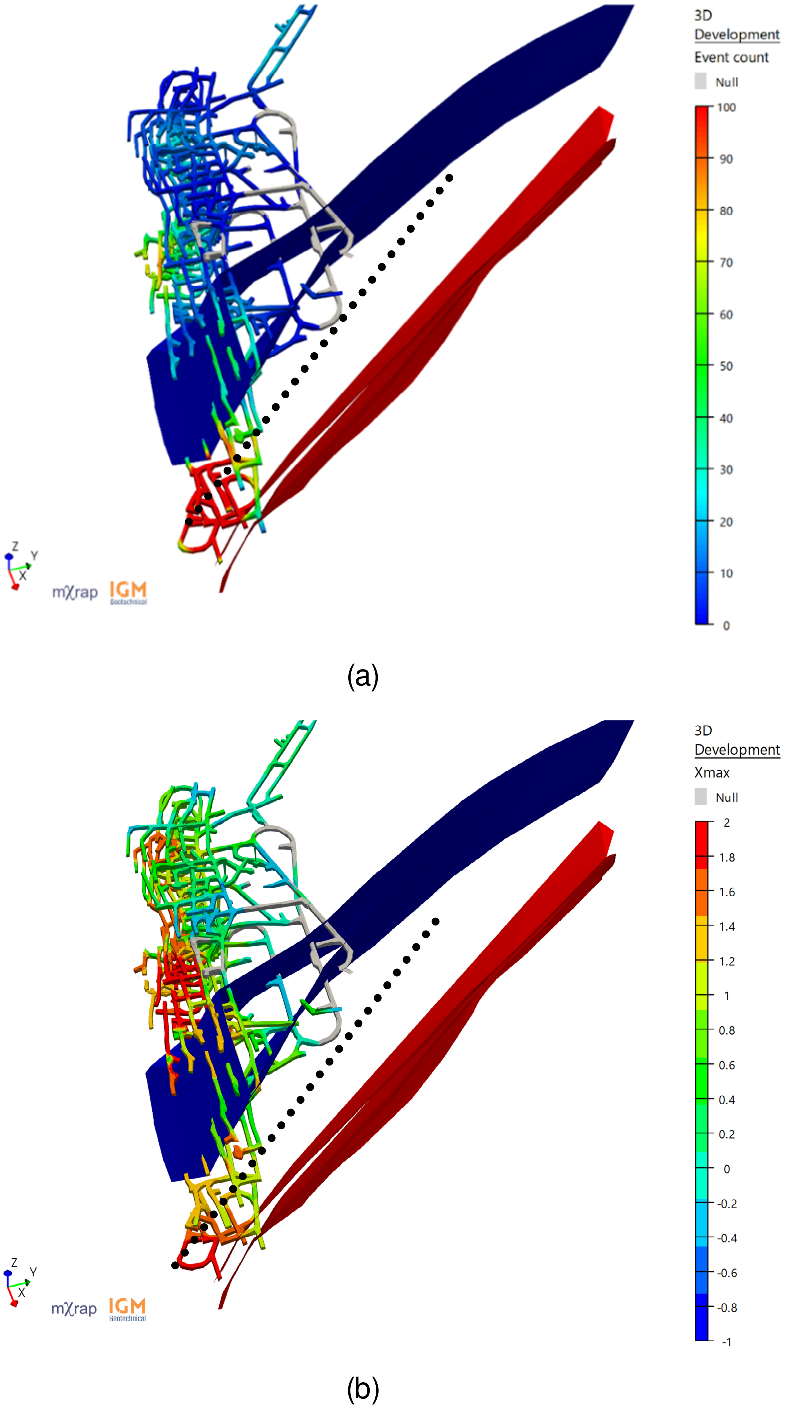
Since 65% of the events investigated is slip-type events it suggests that geological features at Kanowna Belle exert the most significant influence on seismicity. This would suggest that geotechnical controls should be focused on this failure type to ensure best outcomes. It also suggests that in areas where there are no structures but large events, that geological structures are a possibility and needs to be searched for in the databases available to the mine. Note it was assumed that the MTI results were random, and not weighted towards a specific source type.

4 Identifying areas with possible geological structures

In the previous section it was showed that the majority of events at Kanowna Belle mine are related to structures. In this section it will be illustrated that one area in particular is known to be associated with large seismic events. Once this fact is established, It will be showed in Section 5 how it was possible to associate a structure with this area.

Areas with possible structures are identified by investigating areas which have a large amount of events ML > −0.5 and large historical magnitudes associate with them. Areas like these, especially if they show linear spatial hotspots, are the most likely to be associated with geological features. Geological features have a strong spatial influence on the occurrence of seismic events.

For Kanowna Belle mine, one area of particular interest was identified through the methods above. The event count for the area of interest is shown in Figure 6a. Only events ML > −0.5 within 30 m of the development drive is shown. Warm colours indicate areas with a large number of events. In Figure 6b the historical largest magnitude within 30 m from the development drives are shown. Again, the warmer colours show areas with the largest historical magnitudes. The combination of high event count and large magnitude is likely to indicate a missed geological feature associated with seismic events. In Figure 6 the dotted line indicates a possible feature. This will be the feature which is investigated in the next Section through drill holes and other geological and geotechnical data.



(a)

(b)

Figure 6 (a) Event count for all events ML > −0.5 within 30 m from the development drives; (b) Largest historical magnitude (Xmax) within 30 m of the development drives. The dashed line indicates the area where there is both an increase in event count and Xmax

5 Investigating the existence of a potential geological structure

Seismic data is very useful when identifying the existence of seismically active geological features. However, most seismic systems are designed to have locations errors of ~30 m and it is not uncommon to see seismic location artifacts for these systems (Morkel et al. 2022). It is therefore critical to investigate the existence of geological features through other means e.g. Drillhole data, underground observations etc. This section discusses these other methods which are used to confirm the existence of this possible structure.

5.1 Photogrammetry validation

A potential slip plane was identified using Leapfrog 3D Modelling software (Seequent 2023) however, its accuracy necessitates validation.

Handheld measuring devices, such as a compass and an inclinometer were utilised to gather geotechnical data concerning structural discontinuities during underground investigations. Nevertheless, this measurement technique relies on visual inspection and direct measurements conducted by the assessing geotechnical engineer. Consequently, the data obtained may be subject to bias regarding rock mass properties and ratings, influenced by the engineer's expertise and background. Moreover, this method cannot be employed where drives are shotcreted (Lato & Vöge 2012).

Thus, the initial validation process involved comparing the model to photogrammetry data collected in the Kanowna Belle mine over time. Upon preliminary examination, it became apparent that a structure visible across multiple levels in the photogrammetry data (Figure 7) corresponds to the possible structure this study investigates. In Figure 7 the level outlined are indicated by the white lines, and dashed red line indicates the possible geological structure. This structure is associated with a discrete quartz vein which cuts through the tunnel (white feature next to the dotted red line in Figure 7).

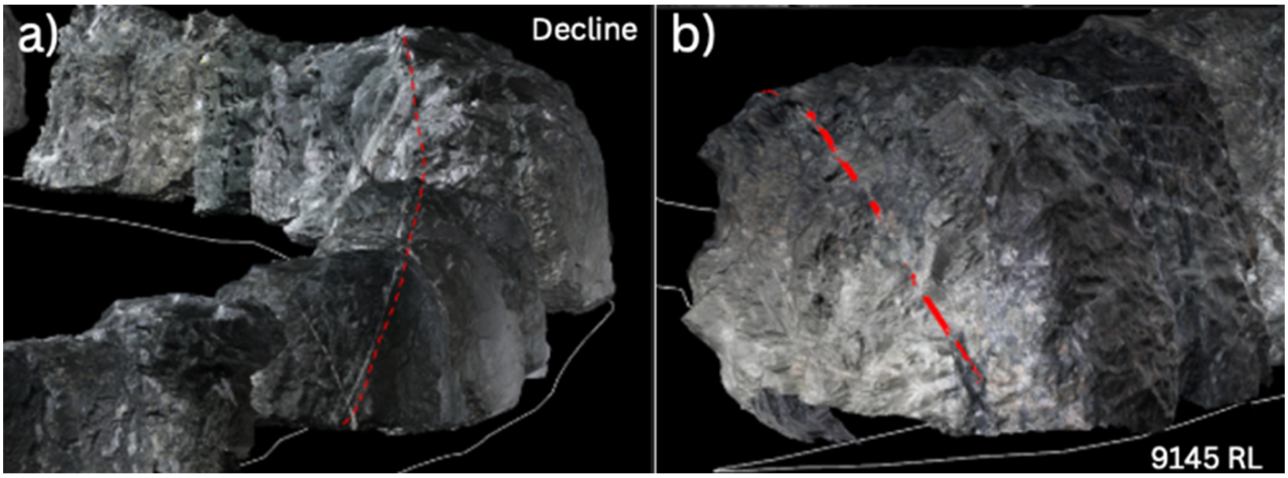


Figure 7 (a) Discrete quartz vein found at the main decline; (b) Discrete quartz vein observed at the 9145 RL. The red dashed line indicates the feature assumed to be the possible geological structure

5.2 Core photos validation

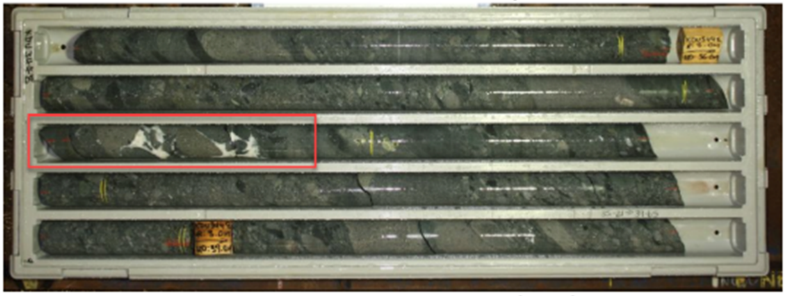
Core photos from drill holes intersecting the fitted plane were carefully examined to verify the presence of the potential slip plane. Each intersecting drillhole's ID and depth were referenced to ensure accurate identification and correlation with the fitted plane. Subsequently, it was determined that five drill holes intersected the proposed plane at different points, offering valuable data for its validation, as depicted in Table 1.

Table 1 Drillholes intersecting the potential slip plane

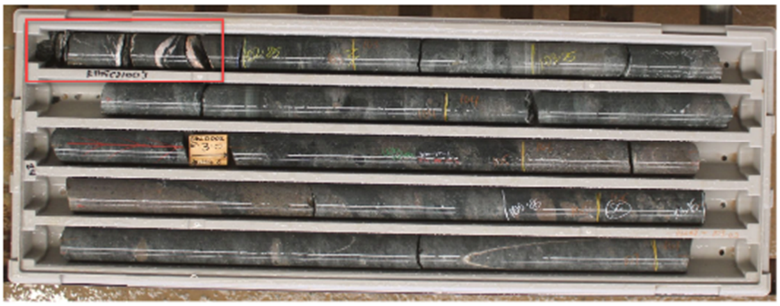
Drillhole ID	Depth
FMGC21002	Approximately 103 m
KDU3448	Approximately 50 m
KDU2021	Approximately 41 m
KDU2086	Approximately 55 m
FMGTT2201	Approximately 10 m

As previously observed, the proposed plane corresponds to a discrete quartz vein, as evidenced by the core photos (Figure 8).

KDU3448 ~ 50m depth



FMGC21002 ~ 103m depth



FMGTT22001 ~ 10m depth

Figure 8 Core photos with the delineated slip plane. The red boxes indicate the areas associated with the possible geological structure

The occurrence of disking around this structure tends to be an indication of a high-stress state, and for Kanowna Belle mine is one of the leading indicators of a highly-stressed tight geological structure.

5.3 Visual investigation of active heading

Only one active development heading intersected the investigated slip plane during this research, enabling observation of the daylight geological structure. Located at the 9680 RL and 57 m from the Moore Felsic Unit, it appeared as the anticipated discrete quartz vein, as depicted in Figure 9.

Figure 9 Discrete quartz vein observed at active heading at 9680 RL

5.4 Final delineation

From the geological data described in the precious sections it is possible to model a wireframe of the structure at hand. This was done in the Leapfrog software and is presented in Figure 10. For clarity, this new structure will be named the Valadares structure.

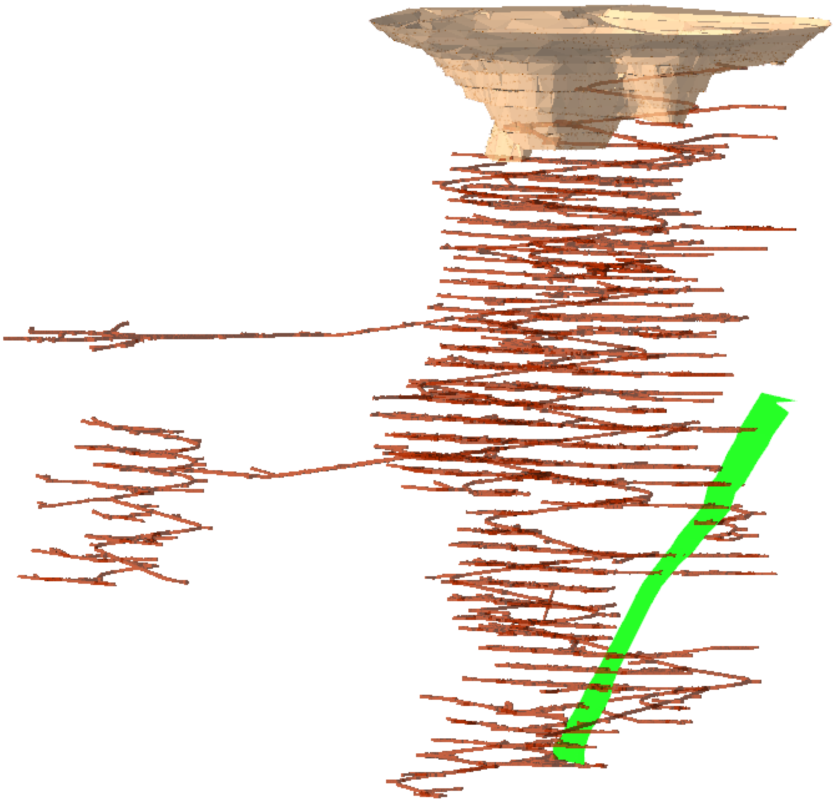


Figure 10 Valadares structure after validation. The green shape represents the refined wireframe surface

The delineation of geological structures based on nodal planes has demonstrated efficiency, particularly in areas where visual mapping could be more feasible, as it offers an estimated location. However, it's crucial to acknowledge that this technique may entail errors, necessitating validation through complementary methods like photogrammetry, analysis of diamond drilling cores, and visual inspection of active headings. Nevertheless, the effectiveness of the overall process hinges on the accessibility and reliability of pertinent data.

6 Overview of the seismic structures at Kanowna Belle mine

It is now possible to review the impact of the Valadares structure with other known structures at Kanowna Belle mine. Figure 11 is the Valadares structure (blue surface) shown with the known hotspots based on event count and largest historical magnitude. This is similar to the plot in Section 4. It can be seen that this structure visually intersects the hotspots (for both event count and Xmax) and therefore has a good visual correlation.

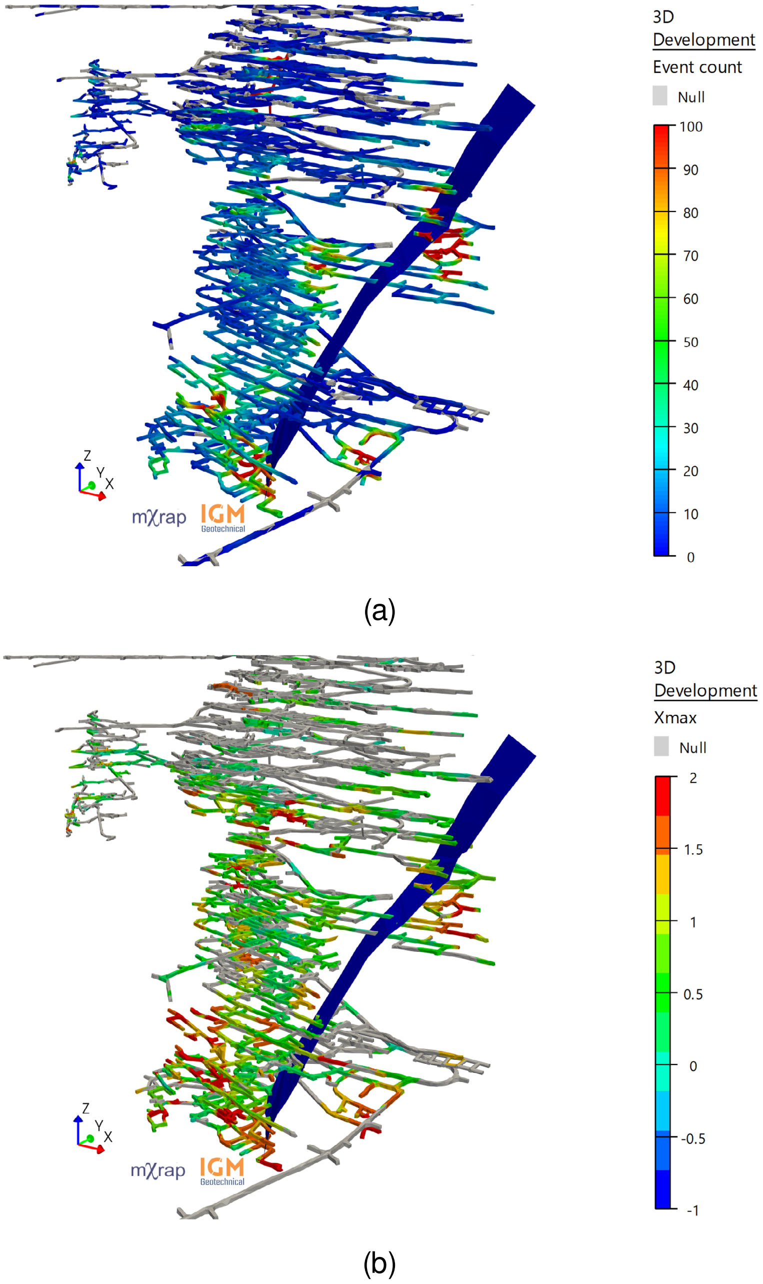


Figure 11 (a) Event count for all events ML > −0.5 within 30 m from the development drives; (b) Largest historical magnitude (Xmax) within 30 m of the development drives. The Valadares structure (possible structure) wireframe is shown as the blue surface

Finally, we investigate the seismic impact of this structure by comparing it with the seismicity of the other known structures. This is achieved by investigating the events associated with the structure based on which events are closest to each wireframe. In Figure 12, a histogram of the event-to-structure distances is shown for known structures. It can be seen that at 40–45 m, the event count reaches background levels. Therefore, this analyses will only consider events within 40 m of a seismic structure. An event can only belong to one structure and this is based on its distance from those structures, with the closest structure it's owner.

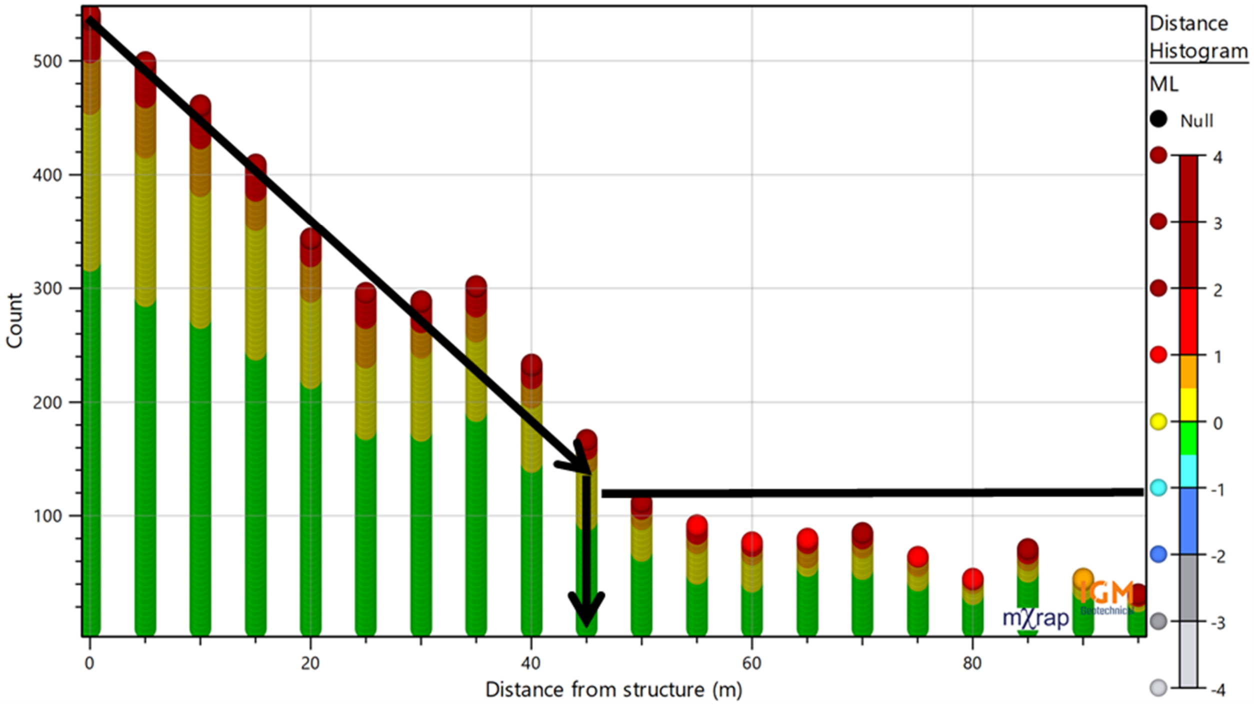
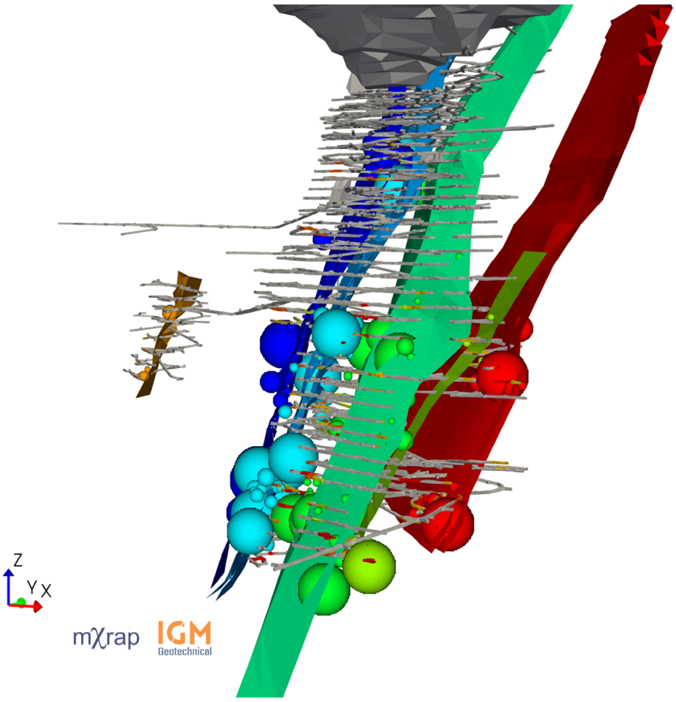


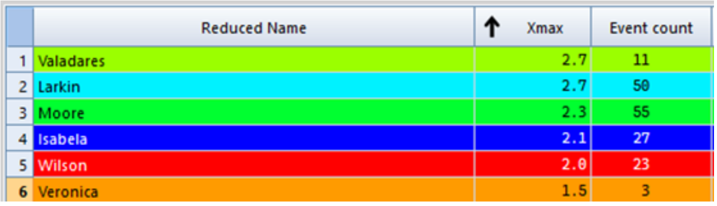
Figure 12 Event-to-structure distance histogram of known structures at Kanowna Bell mine for all events ML > −0.5. Most events happen within ~40–45 m before reaching background levels

Figure 13 is a summary of the known geological structures, with the known events (ML > 1.0) associated with them. Figure 13a is the 3D plot of the seismic events and structures, and Figure 13b is a summary of the structure's seismic history, ranked by historical largest associated events. The table colour for each structure corresponds to the plot surfaces for the structure.

It can be seen that the Valadares structure, although not the most seismic, is associated with several seismic events ML > 1.0 which includes a ML ~2.7 event. This structure can now be considered in geotechnical designs and strategies to minimise the seismic risk associated with these structures.



(a)



	Reduced Name	↑ Xmax	Event count
1	Valadares	2.7	11
2	Larkin	2.7	50
3	Moore	2.3	55
4	Isabela	2.1	27
5	Wilson	2.0	23
6	Veronica	1.5	3

(b)

Figure 13 (a) Plot of events ML > 1.0 for all know structures including the Valadares; (b) Summary of results ranked by Xmax, event count is based on ML > 1.0 events

7 Conclusions and recommendations

The majority of seismic events at Kanowna Belle mine are associated with slip-type events, which suggest the geological features is the dominant source of seismicity. When investigating the seismic data sources, it was found that there are hotspots of seismicity at the mine, which did not correspond spatially with the known seismic structures. This suggested that an unknown seismic structure might be the source of these seismic events.

Even though seismic data is useful, it cannot be used on its own and the findings from the seismic database has to be collaborated by other data sources. In this paper we considered photogrammetry, underground observations and drillhole core to determine a possible structure. Leapfrog was used to create a model of the structure based on these databases which could then be used to evaluate the seismic importance of the Valadares structure (possible structure). It was shown that the Valadares structure has a strong seismic response and should be used in subsequent geotechnical designs and other considerations.

Acknowledgement

This research incorporates findings from a series of analyses supported by Curtin University and Northern Star Resources. Grateful appreciation is extended to all parties involved, especially Sam Ricketts, Raphael Cardoso, Emelisa Perry, Jennifer Thompson, and Simon Thomas.

References

Dahm, T & Krüger, F 2014, 'Moment tensor inversion and moment tensor interpretation', in P Bormann (ed.), *New Manual of Seismological Observatory Practice 2 (NMSOP-2)*, Deutsches GeoForschungsZentrum GFZ, pp. 1–37.

Faradonbeh, RS, Shaffiee Haghshenas, S, Taheri, A & Mikaeil, R 2020a, 'Application of self-organizing map and fuzzy c-mean techniques for rockburst clustering in deep underground projects', *Neural Computing and Applications*, vol. 32, no. 12, pp. 8545–8559. https://doi.org/10.1007/s00521-019-04353-z

Faradonbeh, RS, Taheri, A, Ribeiro E Sousa, L & Karakus, M 2020b, 'Rockburst assessment in deep geotechnical conditions using true triaxial tests and data-driven approaches', *International Journal of Rock Mechanics & Mining Sciences*, vol. 128, pp. 1365–1609, https://doi.org/10.1016/j.ijrmms.2020.104279

Gibowicz, SJ & Kijko, A 2013, *An Introduction to Mining Seismology*, Elsevier, Berlin.

Heal, D 2010, *Observations and Analysis of Incidences of Rockburst Damage in Underground Mines*, PhD thesis, The University of Western Australia, Perth.

Harris, PH & Wesseloo, J, 2015, *mXrap*, version 5, computer software, Australian Centre for Geomechanics, Perth, https://mxrap.com/

Hudson, JA, Pearce, RG & Rogers, RM 1989, 'Source type plot for inversion of the moment tensor', *Journal of Geophysical Research*, vol. 94, pp. 765–774, https://doi.org/10.1029/JB094iB01p00765

Hudyma, MR 2008, *Analysis and Interpretation of Clusters of Seismic Events in Mines,* PhD thesis, The University of Western Australia Perth.

Lato, MJ & Vöge, M 2012, 'Automated mapping of rock discontinuities in 3D lidar and photogrammetry models', *International Journal of Rock Mechanics and Mining Sciences*, vol. 54, pp. 150–158, https://doi.org/10.1016/J.IJRMMS.2012.06.003

Li, Z, Dou, L, Cai, W, Wang, G, He, J, Gong, S, & Ding, Y 2014, 'Investigation and analysis of the rockburst mechanism induced within fault–pillars', *International Journal of Rock Mechanics and Mining Sciences*, vol. 70, pp. 192–200. https://doi.org/10.1016/j.ijrmms.2014.03.014

Malovichko, D & Rigby, A 2022, 'Description of seismic sources in underground mines: dynamic stress fracturing around tunnels and strainbursting', *arXiv*, Cornell University, Ithaca.

Mendecki, AJ 1996, *Seismic Monitoring in Mines*, Chapman & Hall, London.

Morkel, I, Wesseloo, J & Potvin, Y 2019, 'The validity of Es/Ep as a source parameter in mining seismology,' in W Joughin (ed.), *Deep Mining 2019: Proceedings of the Ninth International Conference on Deep and High Stress Mining*, The Southern African Institute of Mining and Metallurgy, Johannesburg, pp. 385–398, https://doi.org/10.36487/ACG_rep/1952_29_Morkel

Morkel, IG, Wesseloo, J & Potvin, Y 2022, 'Seismic event location uncertainty in mining with reference to caving', in Y Potvin (ed.), *Caving 2022: Proceedings of the Fifth International Conference on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 445–460, https://doi.org/10.36487/ACG_repo/2205_30

Ortlepp, WD 1997, *Rock Fracture and Rockbursts: An Illustrative Study*, South African Institute of Mining and Metallurgy, Johannesburg.

Potvin, Y & Wesseloo, J, 2013, 'Towards an understanding of dynamic demand on ground support', in Y Potvin & B Brady (eds), *Ground Support 2013: Proceedings of the Seventh International Symposium on Ground Support in Mining and Underground Construction*, Australian Centre for Geomechanics, Perth, pp. 287–304, https://doi.org/10.36487/ACG_rep/1304_18_Potvin

Seequent 2023, *Leapfrog*, computer software, Seequent, https://www.seequent.com/products-solutions/leapfrog-geo/

Snelling, PE, Godin, L & McKinnon, SD 2013, 'The role of geologic structure and stress in triggering remote seismicity in Creighton Mine, Sudbury, Canada', *International Journal of Rock Mechanics and Mining Sciences*, vol. 58, pp. 166–179, https://doi.org/10.1016/j.ijrmms.2012.10.005

Sugiono, D, Thébaud, N, LaFlamme, C, Fiorentini, M, Martin, L, Rogers, J, … & McFarlane, C 2021, 'Integrating multiple sulfur isotopes with structural analysis unveils the evolution of ore fluids and source of sulfur at the Kanowna Belle Archean orogenic gold deposit, Yilgarn Craton, Western Australia', *Mineralium Deposita*, vol. 56, no. 8, pp. 1471–1490, https://doi.org/10.1007/s00126-020-01032-1

Urbancic, TI, & Trifu, C-I 2000, 'Recent advances in seismic monitoring technology at Canadian mines,' *Journal of Applied Geophysics*, vol. 45, no.4, pp. 225–237.

Varden, R & Esterhuizen, H 2012, 'Kanowna Belle – evolution of seismicity with increasing depth in an ageing mine', in Y Potvin (ed.), *Deep Mining 2012: Proceedings of the Sixth International Seminar on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 211–227, https://doi.org/10.36487/ACG_rep/1201_15_varden

Varden, R, Lachenicht, R, Player, J, Thompson, A, & Villaescusa, E 2008, 'Development and implementation of the Garford dynamic bolt at the Kanowna Belle Mine', *10th Underground Operators' Conference*, Australian Institute of Mining and Metallurgy Melbourne, pp. 95–102.

Vavryčuk, V 2015, 'Moment tensors: decomposition and visualization', in M Beer, IA Kougioumtzoglou, E Patelli, & I S-K Au (eds), *Encyclopedia of Earthquake Engineering* Springer, Berlin Heidelberg, Berlin, pp. 1546–1559, https://doi.org/10.1007/978-3-642-35344-4_288