Deep Mining 2024 – P Andrieux & D Cumming-Potvin (eds)

doi:10.36487/ACG_repo/2465_60

Linking the orientation of seismic response clusters following development blasting, the stress regime and large-scale structures

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Abstract

As mines get deeper, seismic responses to drift development blasts become critical and can result in major operational constraints. Therefore, understanding seismic hazards associated with development blasting is crucial. This paper investigated 228 seismic response clusters following development blasting for a deep sector of LaRonde mine (Angico Eagle Ltd) in Canada. The orientation of seismic response clusters was investigated. A plane-fitting algorithm using principal component analysis (PCA) was used to define the seismic response clusters' orientation. The analysis showed that the alignment of the seismic response clusters is not random. Most clusters are sub-horizontal and in the direction of the principal stresses (σ_1 and σ_2). The orientation and seismic moment of clusters were then linked to the stress regime and large-scale structures to identify possible failure mechanisms.

Keywords: *seismic response clusters, deep mining, blasting, stress, structures*

1 Introduction

Seismic risk is a function of stress, geological structure and the influence of the mining environment, as these factors influence the location, magnitude and frequency of seismic events (Tierney et al. 2019). Managing seismic risk associated with drift development blasting is a major challenge for deep and high-stress mining. Seismic risk can significantly impact personnel and equipment safety, meeting production goals and, consequently, a mine's profitability. Quantifying seismic hazards requires understanding seismic events' spatial distribution, magnitude and frequency. Figure 1 presents a schematic local seismic response following a development blast.

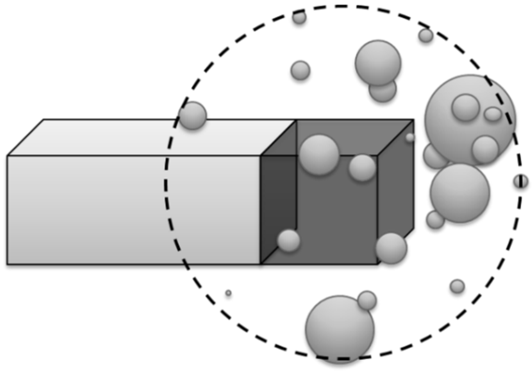

Figure 1 Seismic response to a development blast in an underground mine

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Previous work has focused on delineating seismic response clusters, observing that well-localised seismic events exhibit strong spatial clustering (Dodge & Sprenke 1992; Eremenko et al. 2009; Gibowicz & Lasocki 2001; Hudyma et al. 2003; Kgarume et al. 2010; Kijko et al. 1993; Malek & Leslie 2006; Mendecki & Lynch 2004; Urbancic et al. 1992; Vallejos & McKinnon 2010; Woodward et al. 2017). Assuming that seismicity is fundamentally the result of rock mass failure, each group of events, such as the seismic response to a developmental blast, potentially represents an individual seismic source mechanism, as determined by a unique combination of constraints, structures and influences of the mining works (Hudyma et al. 2003).

Therefore, analysis of the orientation of seismic response clusters can reveal to which mechanism or structure a seismic response is linked. The quantification of seismic events' spatial distribution allowed the improvement of quantification of the seismic hazards. This paper studies the orientation of seismic response clusters following development blasts from the LaRonde deep underground mine. A detailed case study of 228 development blasts allowed us to investigate the relationship between the orientation and intensity of seismic responses to drift development and the sector's structural and stress regimes to better understand the potential underlying mechanisms.

1.1 Influence of a stress regime

The orientation of major principal stresses influences the orientation of seismicity. Numerous microscopic-scale studies have demonstrated that microcracks will preferentially develop in the direction of the maximum principal stress in a compressive stress field, resulting in anisotropic material properties (Kemeny & Cook 1991). As the stress level increases, new fractures are created. Existing fractures also propagate until fractures intersect and interact with each other. At the laboratory scale the propagation of fractures is accompanied by acoustic wave emissions, whereas at the field scale it might be accompanied by micro-seismic events (Falmagne 2001). As the magnitude of in situ stress increases, natural fractures become narrower and rock failure is increasingly dominated by new stress-induced fractures, frequently developing parallel to the stresses at the boundary of underground openings (Kaiser et al. 2000). Stress-induced fractures are mainly parallel to the maximum principal stress around the drifts (Cai et al. 2001). It is one of the most apparent damage features near tunnels in brittle hard rocks (Cai et al. 2001).

1.2 Influence of structures

Major shear structures also influence stress orientation variations. Therefore, considering the large-scale structures in seismic responses' orientation analysis is also essential for better consideration of stress perturbation. Shear zones and faults have been linked to mining seismicity by many authors (Chinnasane et al. 2012; Cochrane 1991; Durrheim et al. 1998; Goulet et al. 2024; Heal 2010; Morissette & Hadjigeorgiou 2019; Morissette et al. 2016; Ortlepp 1992; Simser 2022; Urbancic et al. 1993; Vallejos & McKinnon 2008). Different studies have shown the impact of interpreted fault corridors on the location of events (Cochrane 1991; Morissette et al. 2016; Ortlepp 1992; Urbancic et al. 1993). Cochrane (1991) demonstrated that many violent and nonviolent failures occur near late-stage faults in the Sudbury District (Ontario). Ortlepp (1992) states that large-magnitude seismic events ($M_L > 2.5$) are often associated with fault slip. The distribution of seismicity can also make it possible to robustly obtain the general trends of faults in the rock mass, according to Urbancic et al. (1993). Morissette et al. (2016) modelled the elastic differential stress for a mined-out shape. They observed that large events ($M_N > 2$) crudely matched the location of some existing shear faults when in certain stress conditions at the Creighton deep mine (Ontario, Canada). Therefore the orientation of a cluster of seismic events could represent the orientation of these corridors. Goulet et al. (2024) demonstrated that structural features such as specific shear corridors were correlated to the intensity of seismic response clusters during development blasts set 3 km below ground at the LaRonde mine.

2 Case study and methodology

The selected case study is a portion of the western sector of the LaRonde mine, located in the Abitibi-Temiscamingue region in Quebec, Canada. The gold-rich volcanogenic massive sulphide deposit of

LaRonde has been mined since 1988, and its current mine life is until 2036 (Agnico Eagle 2023). The main mining methods used are longitudinal and transverse longhole open stoping with a production rate between of 5,000 and 6,000 tonnes hoisted daily. The studied area is defined by three mining levels (299W, 302W and 305W) located around 3 km under the surface in the west sector (Figure 2). The study period extents from 1 August 2018 to 13 December 2019. Goulet et al. (2024) detail the criteria for choosing this specific sector and period, which are:

- The study area is outside the zone of influence of the mining stopes in terms of redistribution of stress and induced seismicity.
- Different levels of seismic hazard, including high seismic hazard, are observed during drift development.
- The variability of geology and structures in the area is observed and the available data analysed.
- An identical blasting design is used.
- The quality of seismic data is sufficient.
- A strong correlation exists between seismicity and the development of mining drifts.

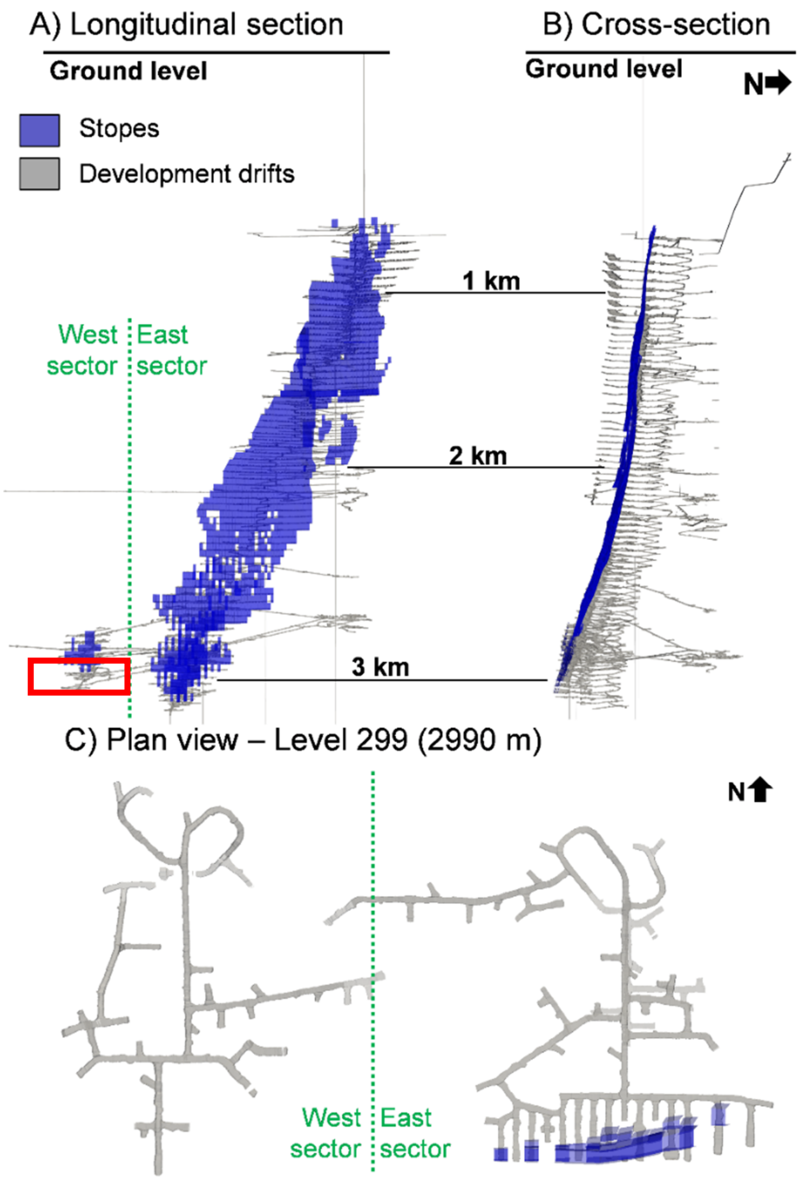

Figure 2 Longitudinal section of the LaRonde mine stopes as of December 2019

As the seismic network's configuration has a large impact on seismic event location accuracy and may produce an apparent planarity of clusters, the coverage of the seismic system, the location accuracy and the seismic system's sensitivity were investigated to ensure adequate seismic data quality. In the studied sector, 14 uniaxial 50 Hz accelerometers, three triaxial 50 Hz accelerometers and one triaxial 15 Hz geophone were used to record the seismic events. The coverage of the LaRonde west mine seismic system for the period studied is acceptable as it corresponds to industry practice regarding bandwidth criteria, the uniaxial:triaxial sensor ratio and inter-sensor spacing. In the study area the median location error is 4 m, with a 90th percentile of 7.2 m. More details on the seismic data quality can be found in Goulet et al. (2024).

2.1 Large-scale structures

The mine is located 2 km north of the Cadillac regional fault zone (CFZ), a 250 km-long, south-dipping, sub-vertical fault zone associated with intense hydrothermal alteration (Card 1990; Daigneault et al. 2002; Norman 1946). Numerous CFZ-related shear zones are encountered in the LaRonde mining drives. These mine-scale shear corridors are mainly oriented east–west and are steeply south-dipping in the studied sector. Their geometry fluctuates laterally and vertically along their course, extending for hundreds of metres.

One major shear zone is known to cross all mine levels and is associated with a wide (>15 m) corridor of highly fractured rock: the 700 fault. Other shear zones are also observed at the mine but are of lesser amplitude than the 700 fault and contain less or no crushed material; the intensification of schistosity characterises them more. The main deformation event in the area has created this steeply south-dipping schistosity. At the mine site, this inherent schistosity is present everywhere in the rock mass along foliation with variable intensity, depending on its proximity to the ore zone and lithologies. It gets stronger closer to the mineralisation and in the shear corridors.

Secondary structures (disturbed schistosity) near shear corridors in the studied sector have been identified by Goulet & Grenon (2024). This disturbed schistosity is defined by a dip direction ranging between 190 and 230°. The disturbed schistosity planes were not observed in shear corridors but in their surroundings.

2.2 Stress regime

The estimated orientation and magnitude of the in situ principal stresses at LaRonde are based on measurements obtained from overcoring carried out by CANMET (1999) at 1,460 and 1,500 m below the surface, and Corthésy & Leite (2006) at 2,150 m beneath the surface. The major and intermediate principal stresses (σ_1 and σ_2) are sub-horizontal, while the minor principal stress (σ_3) is sub-vertical (Table 1).

Table 1 Major principal stresses of the historical model at the LaRonde mine

Principal stress	Orientation	Relationship	Magnitude (3 km below surface)
σ_1	North–south, sub-horizontal	$1.62 \cdot \sigma_v$	131 MPa
σ_2	East–west, sub-horizontal	$1.34 \cdot \sigma_v$	109 MPa
$\sigma_3 = \sigma_v$	Sub-vertical	0.027 MPa/m	81 MPa

As stress-induced fractures are mainly parallel to the maximum principal stress around the drifts (Cai et al. 2001), horizontal stress fractures are expected (Figure 3).

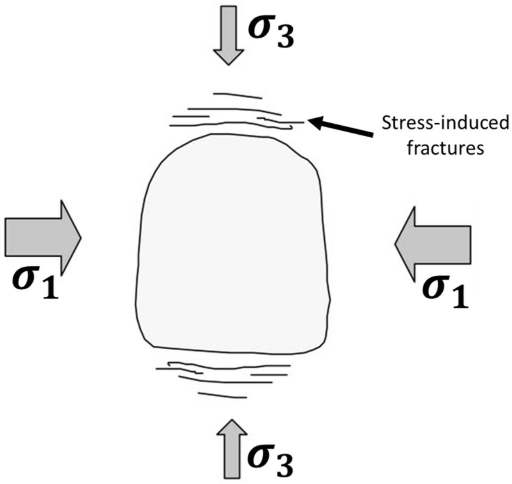

Figure 3 Schematic representation of stress-induced fracturing near underground openings in a high-stress environment. The fractures are parallel to the roof because the major principal stress is parallel to that surface (modified from Cai et al. 2001)

The major principal stress is approximately perpendicular to the main large-scale structures such as ore lenses, lithological contacts, shear corridors and schistosity. Mining stopes greatly influence stress redistribution since the major principal stress is horizontal and oriented along a north–south axis while the deposit is aligned along an east–west axis. No stope was mined on the three levels studied over the analysed period, while only two stopes were mined on the immediate upper level. Therefore the zone of interest was arguably outside the zone of influence of the stopes due to the absence of production blasts. The impact of stopes on stress is not considered further in this study.

The presence of schistosity greatly influences stress redistribution and it is appropriate to consider the orientation of the drifts in relation to the schistosity to better understand the impact of stress orientation on the seismic responses' orientation. The angle of intercept between the direction (strike right) of the schistosity and the drift orientation (ψ — angle drift schistosity) is used to define the orientation of the schistosity with respect to the drift segment orientation (Figure 4).

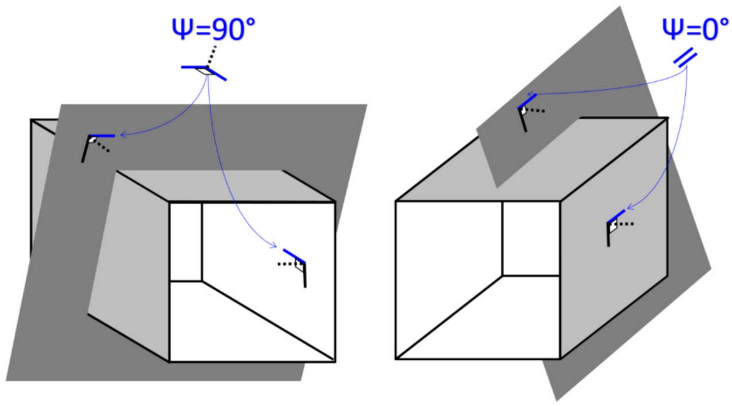

Figure 4 Angle between the direction (strike right) of the schistosity and the orientation of the drift (ψ)

2.3 Delineation of seismic response from development blasts

The region of stress disturbance induced by mining around drifts is generally in the order of several excavation radiuses (Kirsch 1898). This zone of influence corresponds to the theoretical spatial extent of a blasting-induced seismic response. Kuzyk & Martino (2008) mentioned that the disturbed zone around an excavation extends from two to five times the distance of its radius. In the case of a development drift of 5 m in diameter, the disturbed zone would be between 5 and 12.5 m. Brown (2018) recalled the importance of considering the location error of seismic events to define the radius around the blast, which is necessary to delimit the seismic responses to blasts. Woodward et al. (2017) suggested that the primary considerations should be time and space in selecting a methodology identifying seismic responses to mining activities. Isolating seismic populations using a fixed spatial distance from a point of interest is common (Woodward et al. 2017). Although imperfect, this technique may prove sufficient for studying seismic responses to development blasts, where the reaction is usually local and concentrated around the blasting of mining drifts. This is the case for seismic responses to development blasts for the levels studied during the analysis period.

Seismic events located within a 40 m radius around the development blast and within a time window of 11 hours following that blast were selected to delineate the seismic responses. These parameters allow the complete local seismic response of most blasts to be adequately delineated, considering seismic database quality for the case study and limiting interaction with mining activities. Note that the blasting windows are not considered. Most of the seismic events occurred in a radius of 22.5 m of the development blast (a drift radius of 2.5 m plus an influence radius of 10 m plus a maximum location error for events in the study of 10 m), which is expected for local seismic response. Development blast responses that could have interacted with other responses based on the radius and time window used were not considered for this analysis. In addition, all drift blasts within 24 hours of any of the 53 production blasts in the entire western mine sector during the study period were excluded from the analysis. That gives a total of 449 development blasts studied.

2.3.1 Orientation of clusters

The spatial orientation of seismic response clusters refers to the orientation of a plane on which the events are aligned. A plane-fitting algorithm using principal component analysis (PCA) was used to determine the orientation of each plane. PCA fits a linear regression through the point cloud and minimises the perpendicular distances between the points and the fitted plane model (Joliffe 1986). Three main components express this regression. The coefficients of the first two components define vectors that form the plane's basis. The third principal component is orthogonal to the first two and represents the normal to the plane. The three components are adjusted to capture the maximum variance in the sample in 3D space. The first two components therefore capture more variation than the last.

Thus this algorithm traces a plane in space by grouping all seismic events delineated as a seismic response to a development blast. Figure 5 shows the plane formed by the first component (red vector) and the second component (green vector). The third component is orthogonal to them (blue vector).

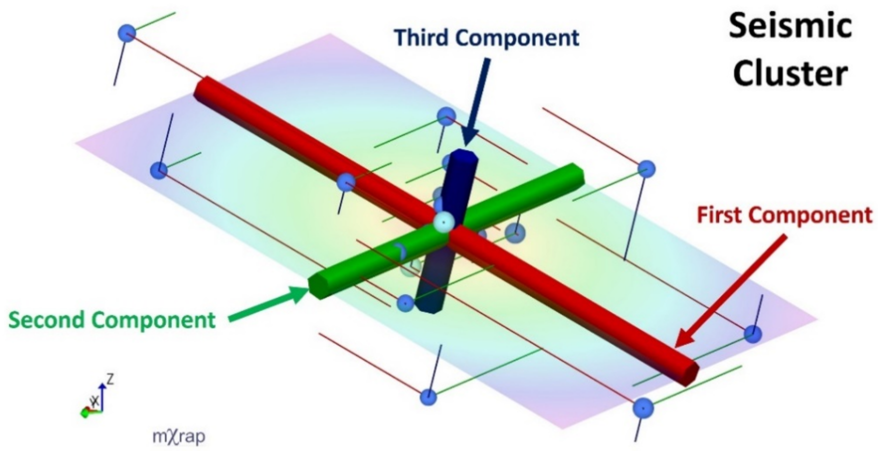

Figure 5 Illustration of the adjustment of a plane through events defining a seismic response to development blasting of a drift segment using a principal component analysis method

A minimum of three seismic events is theoretically necessary to draw a plane. For this study a plane was determined for each seismic response following a development blasting with five events or more. All seismic events following a single development blast were considered as being part of the same cluster.

When the cluster is planar the spatial variance will be strongly expressed by the first two components of the PCA analysis (red and green vectors in Figure 5). It is possible to determine the adjustment quality by the proportion of spatial variance of the sample explained by the first two components. Considering the uncertainty related to the seismic events' location and the small analysis radius around the blast used, the spatial variance of the seismic response clusters is likely to be relatively high. Thus achieving a large proportion of the variance explained by the two principal components isn't easy. It was deemed not very useful to perform a variance analysis, and that focus would instead be on the number of available clusters.

2.3.2 Intensity of oriented seismic responses

The source parameters of individual seismic events, which are location, time of occurrence, seismic energy, seismic moment and source radius, can be used to quantify the seismic responses' intensity. Goulet et al. (2024) describe five parameters using these sources parameters to quantify seismic events (Table 2). These parameters could be correlated differently and are not equivalent.

Table 2 Quantitative parameters defining the intensity of the seismic responses following the development blasts

Parameters to quantify seismic responses' intensity
Number of seismic events
Maximum moment magnitude (MW) of the seismic events
Logarithm (sum of seismic moments [MO] of events) (Nm)
Logarithm (sum of radiated energy of events) (J)
Sum of the radii of the source of each seismic event (m)

In this paper, the maximum MW event is the parameter used to quantify the intensity of each seismic response cluster. Based on experience at the mine site, it is assumed that drift damage is generally caused by events of MW $\geq$ 0.4. However, events of MW $\geq$ 0 have been known to generate damage in mining drifts when they were non-reinforced at the mine site. The intensity of the seismic response can be classified into two categories: it contains an event MW $\geq$ 0, or it does not.

3 Results

3.1 Seismic responses to development blasting

3.1.1 Orientation of seismic response clusters

Figure 6 shows all the planes obtained by PCA analysis for clusters having at least five seismic events. A total of 228 planes could be obtained, corresponding to 51% of the blasts investigated (228/449). Since these planes are oriented in space it is possible to visualise their orientation in a stereonet (Figure 7). The iso-contours of the stereonets represent the density of the poles and the scale shown in Figure 7 remains the same for all subsequent stereonets in this paper.

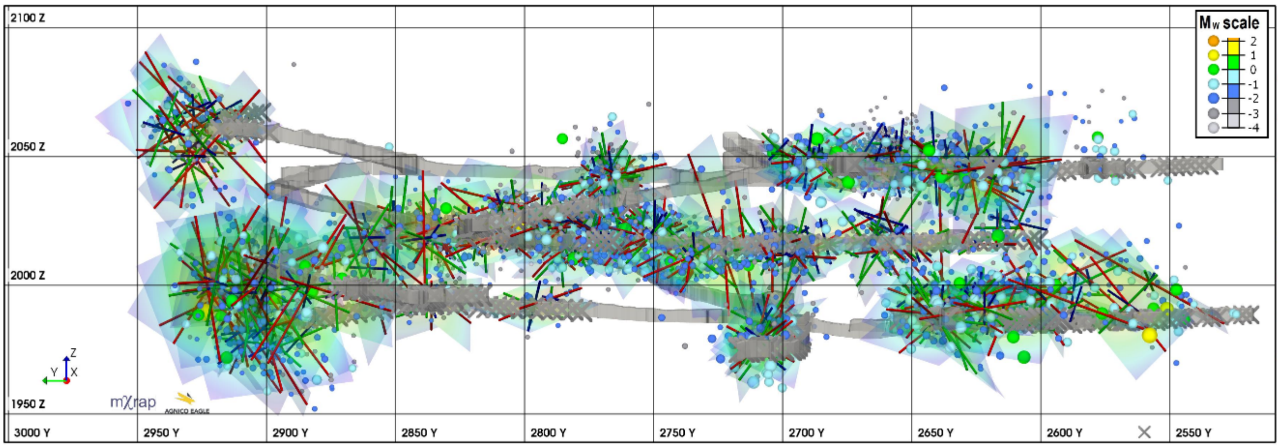

Figure 6 **Planes obtained by principal component analysis analysis for all seismic response clusters comprising five or more events for a radius of 40 m around the blast for a period of 11 hours post-blasting (228 planes)**

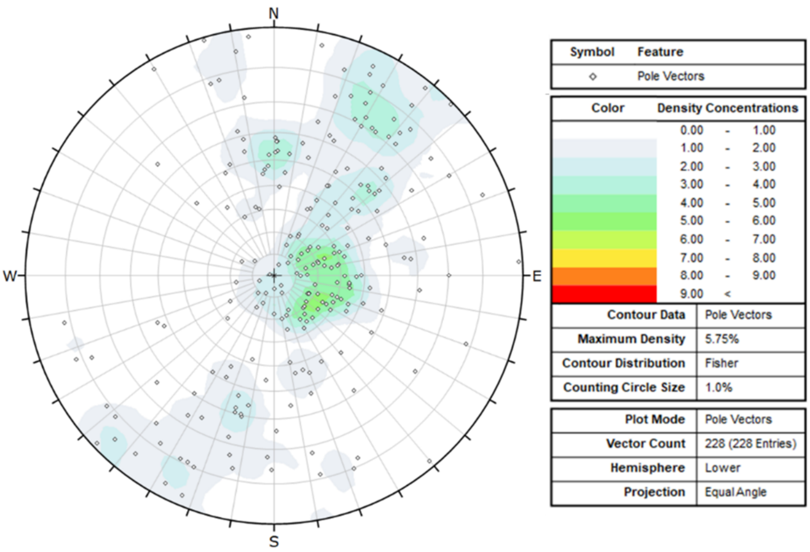

Figure 7 **Stereonet of planes adjusted to clusters having at least five seismic events (228 planes)**

Limitations of the seismic network regarding event location accuracy have been addressed in Section 2. Regardless of the remaining uncertainties, investigating cluster orientation is believed to provide insightful information for mine design. All the poles of the seismic response being grouped together, it is possible to state that the alignment of seismic response is not random. This observation suggests that a particular mechanism or a given structure plays a role in controlling the orientation of seismic response to development blasting. Most of the clusters in the case study are sub-horizontal (Figure 7 – poles in the middle of the stereonet), while some are in the south-southwest portion of the stereonet, the northeast portion and the north portion. Among the 228 clusters, 40% (92/228) are dipping at less than 40°.

3.1.2 Intensity of oriented seismic response clusters

To maximise understanding of the seismic responses to development blasting, the combined analysis of the intensity of the seismic response clusters and the orientation of the seismic response clusters is undertaken. Figure 8 presents the stereonet of the poles of the 228 clusters whose orientation have been defined. The poles' markers have been adjusted to the maximum seismic moment magnitude classification of the seismic response clusters.

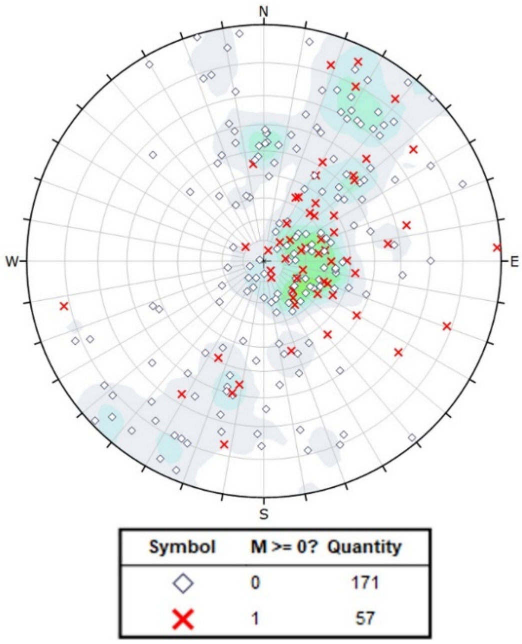

Figure 8 Stereonet of seismic cluster planes coloured by their moment (MW) classification for intensity (228 planes)

Most high seismic moment clusters (containing an event of MW ≥ 0) are sub-horizontal or in the north-northeast portion of the stereonet. A third (34%; 31/92) of the 92 sub-horizontal clusters (dip < 40°) contain an event of MW ≥ 0. From all seismic responses containing an event of MW ≥ 0, 54% (31/57) are sub-horizontal. Few high seismic moment responses are observed in the southeast and east-northeast sections of the stereonet. The seismic responses in the north portion of the stereonet are mostly characterised by a low seismic moment.

3.2 Influence of the orientation of principal stresses

As previously discussed, the majority of the seismic response studied resulted in a sub-horizontal plane. Stress-induced fracturing was, therefore, deemed a plausible mechanism along this orientation since it is parallel to the maximum principal stress around the drifts. To consider the impact of stress redistribution along schistosity planes at the mine, the seismic responses' orientation according to different angle classes of ψ are illustrated in Figure 9.

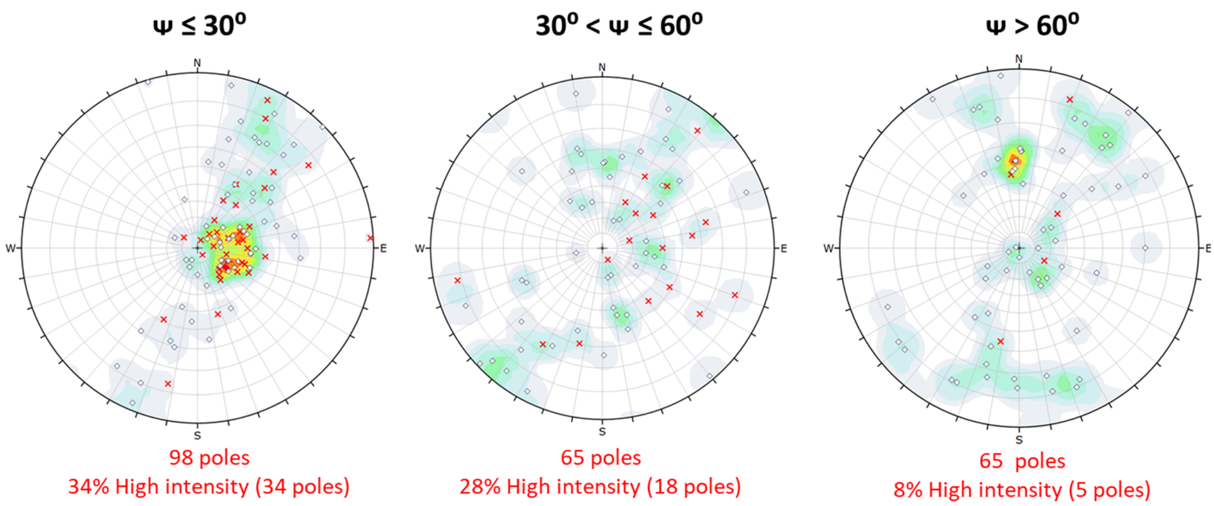

Figure 9 Poles of 228 seismic responses to development blasting according to the angle of intercept between the orientation of the schistosity and the drift

When the excavation is parallel to the schistosity planes (ψ ≤ 30°), 34% of the clusters have a high seismic moment. The seismic clusters are well aggregated in the stereonet into three main orientations: the centre, south-southwest and northeast portion of the stereonet. The cluster representing sub-horizontal seismic responses is the more populated and contains the most high-intensity responses. In fact, among the seismic response clusters for which ψ ≤ 30°, 55 have a dip <40°, representing 56% (55/98) of all seismic response clusters. Among these 55 clusters, 23 (42% of 55) have a high seismic moment, representing 68% (23/34) of the total of the high-intensity responses of the 98 poles of this stereonet.

The clusters are more dispersed for the drift segments for which 30° < ψ ≤ 60°. Cluster orientations seem to be a transitional stage from cluster orientations when the excavation is parallel and perpendicular to schistosity.

For drifts perpendicular to schistosity (ψ > 60°), only 8% of seismic responses contain an event of MW ≥ 0. The seismic responses are mainly sub-horizontal as well as in the north and south portions of the stereonet. They are less well clustered than when the drift is parallel to the schistosity. High seismic moment intensity responses are three to four times less expected in drift perpendicular to schistosity (ψ > 60°) than in other orientations. The orientation of the drift seems to influence the seismic moment intensity of seismic responses. Most of the responses in the north part of the stereonet occur when the drift is excavated perpendicular to the schistosity; they are all low seismic moment responses.

3.3 Influence of proximity of large-scale structures

The variation in orientation of the seismic responses linked to the blast location regarding the shear corridors can be easily visualised into two stereonets: either the blast is inside or outside a shear corridor (Figure 10). In both cases the seismic responses are not mainly aligned along the general orientation of shear corridors, which follow an east–west axis strongly dipping south (poles would be in the north portion of the stereonet). Only some poles of the seismic responses are oriented according to the main orientation of shear corridors.

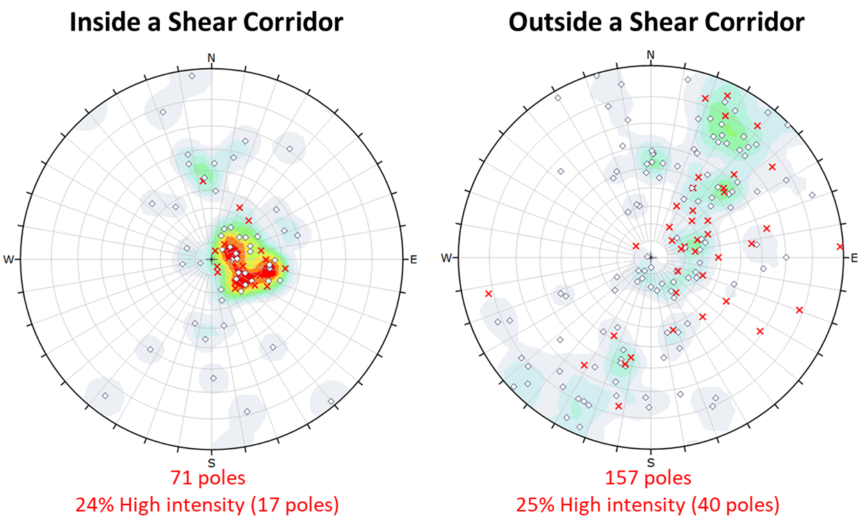

Figure 10 Poles of 228 seismic responses according to the location of the development blast in relation to interpreted shear corridors

The quasi-total of seismic responses of a development blast located in a shear corridor is sub-horizontal. In addition, all high seismic moment responses occurring in a shear corridor are sub-horizontal. The same proportion of high seismic moment responses are observed outside a shear corridor (inside 24%, outside 25%) but the clusters are more scattered in orientation. The proximity to a shear corridor does not seem to influence seismic response intensity. The seismic responses outside a shear corridor are mainly sub-horizontal or have their poles in the north-northeeast or south-southwest portion of the stereonet.

3.4 Summary of results

Previous sections showed the influence of both the orientation of the development drift and the proximity of large-scale structures. Figure 11 shows the combined analysis of both parameters to identify how these interact with each other regarding seismic response clusters orientation.

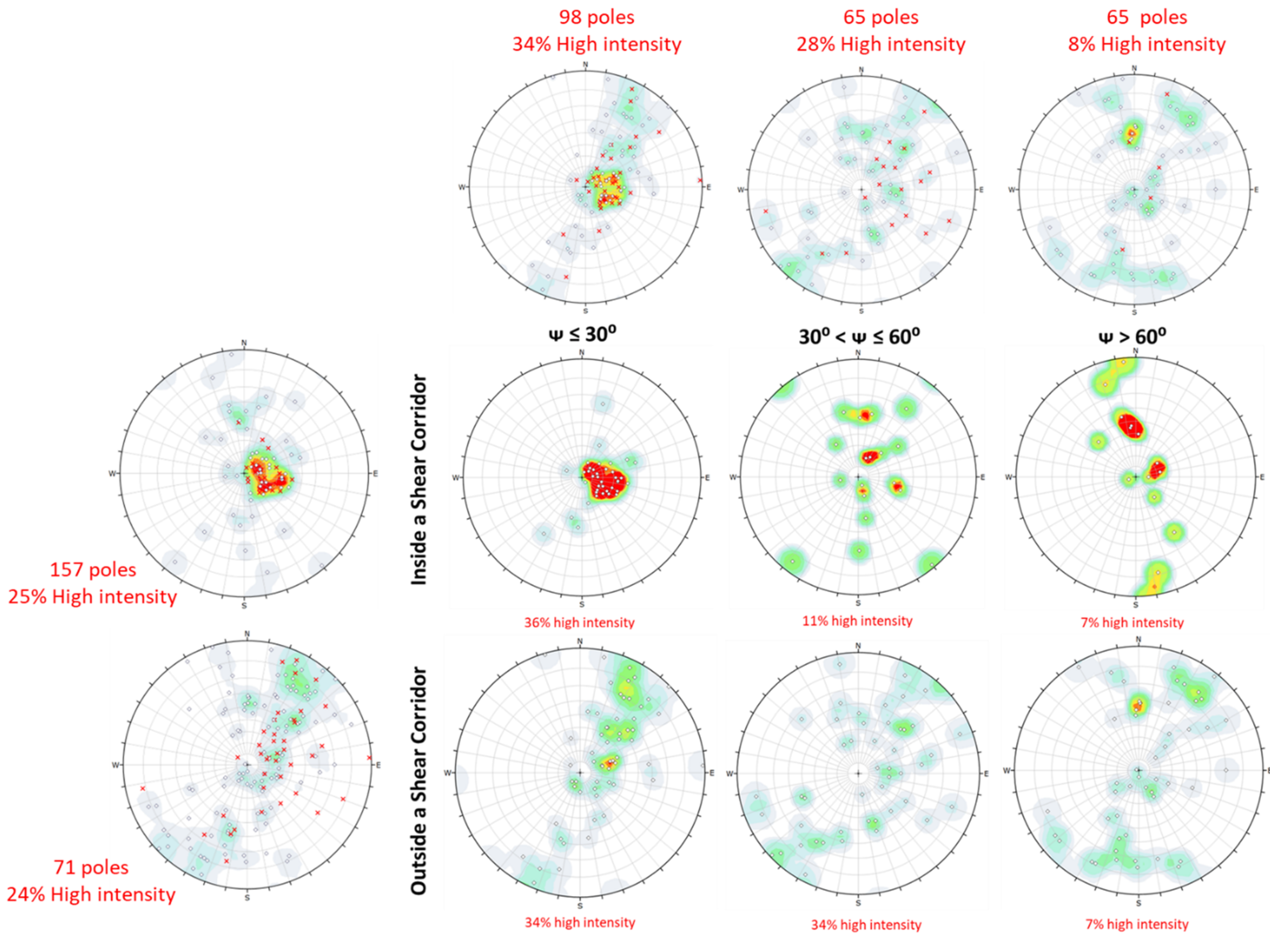

Figure 11 Composite plot of 228 plane pole solutions separated by drift orientation relative to schistosity (ψ) and blast location relative to a shear corridor

For the drifts located inside a shear corridor there are few seismic responses in the north-northeast portion of the stereonet for all angles of ψ considered, as observed previously. When that drift is, in addition, parallel to the schistosity (in this case for ψ ≤ 30°), the seismic response seems to always occur horizontally.

When the excavated drift is located outside a shear corridor there is a slight shift from the north-northeast to north and south-southwest to south portions of the stereonet from when the drift is developed from parallel to perpendicular, relative to schistosity. That shift might be due to stress or the way it is redistributed.

When the drift is developed perpendicular to schistosity (ψ > 60°), the seismic response orientations are similar whether the drift is located inside or outside a shear zone. The seismic responses are mainly concentrated in the north–south portion of the stereonet, with some sub-horizontal responses. The proportion of high seismic moment responses remains the same inside or outside a shear corridor. It might indicate that the same failure mechanism applies when the drift is excavated perpendicular to schistosity, regardless of its location to a shear zone.

Figure 11 shows the high seismic moment responses occurring in drifts for which 30° < ψ ≤ 60° mainly occur in segments outside a shear corridor rather than inside. That difference might be explained by the mechanism involved.

4 Analysis and discussion

Analysis has shown that seismic responses to development blasts are mostly not oriented along the interpreted shear corridors in the studied sector. Almost none of the seismic responses to a development blast, located in a shear corridor, are aligned along these corridors. These observations show the complexity of the mechanisms linked to seismic events and responses to development blasting. The lack of alignment between seismic events in shear corridors and the orientation of the shear corridors was put forward by De Santis et al. (2019). The lack of alignment could also be partly linked to the uncertainty of event source location.

The orientation of the seismic responses relative to the angle formed by the orientation of the drift and the schistosity can arguably be partly explained by the orientation of the major principal stress. It is possible that when the rock mass is strongly affected by schistosity, like in a shear corridor, and under high stresses, the redistribution of stresses generates seismicity which is linked to a deformation similar to a buckling mechanism. Turcotte (2014) proposed this buckling-like mechanism to explain the greater severity and occurrence of rockbursts in drifts parallel to the schistosity. Turcotte (2014) also suggested that when the energy of a seismic event is released the deformation wave induces a failure in the rock mass similar to buckling, except that the failure is essentially instantaneous. The seismic response could, therefore, be associated with the progression of the breakage of the rock mass perpendicular to the shear planes linked to schistosity or fault zones, as illustrated in Figure 12.

Buckling has already been shown to be more severe in a drift parallel to schistosity (Mercier-Langevin & Hadjigeorgiou 2011; Mercier-Langevin & Wilson 2013; Karampinos et al. 2015). Logically this buckling-like mechanism also mainly affects the drifts parallel to schistosity. That would explain why the cluster representing horizontal seismic responses is more populated when the drift is parallel to the schistosity planes ($\psi \leq 30°$). This study showed that seismic responses of a development blast located in a shear corridor are mainly sub-horizontal. Shear planes such as the one related to schistosity are closer to each other in shear zones, making the drift segments in the shear corridor more prone to this buckling-like mechanism. In addition, when the drift is parallel to schistosity and located in shear zone, the seismic response is always sub-horizontal.

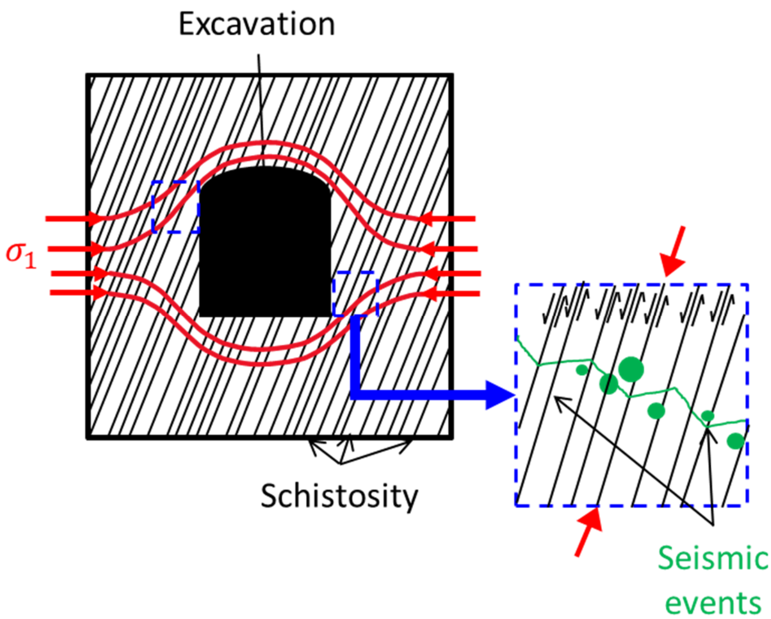

Figure 12 Buckling-like mechanism related to fracture-generating seismic events perpendicular to schistosity (ψ = 0°) in a rock mass strongly affected by schistosity

It has been demonstrated that the seismic response orientations are similar whether the drift is inside or outside a shear zone for drifts developed perpendicular to schistosity ($\psi > 60°$), mainly north–south. Thus it is reasonable to assume that the same failure mechanism applies when the drift is excavated perpendicular to schistosity, regardless of its location to a shear zone. This orientation corresponds to schistosity plane orientation.

When the schistosity is less severe (larger spacing between planes), as in outside shear corridors, or when drifts are not excavated parallel to schistosity, the seismic responses could be linked to shearing along disturbed or undisturbed schistosity planes. When the drift is developed perpendicular to the schistosity there is a certain deconfinement of the schistosity planes in the face of the excavation (Figure 13a). Before excavating, the clamping of these planes is associated with the major principal stress, parallel to the normal to the schistosity planes. When deconfinement occurs the schistosity planes slide over each other by shearing, generating seismicity along these planes. Excavating parallel to schistosity also decreases the deconfinement of the schistosity planes in the walls rather than in the face (Figure 13b). When schistosity planes are not close enough, as in outside a shear zone, a shearing mechanism is more probable than a buckling-like mechanism.

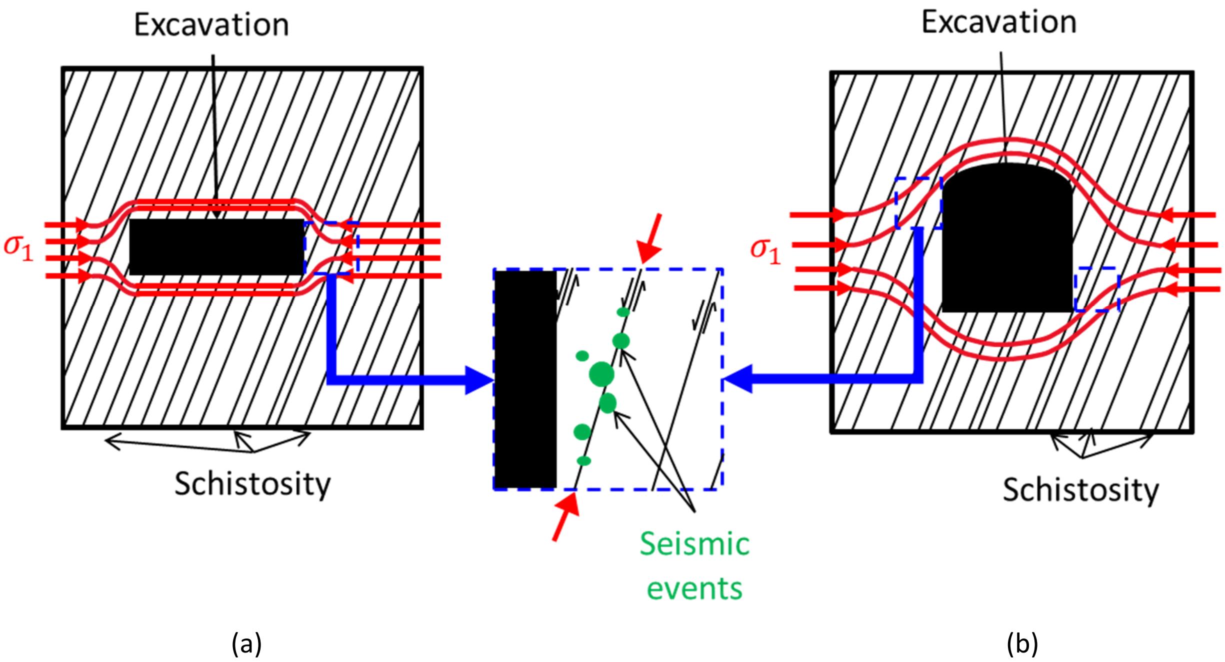

Figure 13 Seismic responses related to the shearing mechanism in (a) drifts perpendicular to schistosity (ψ = 90°) and (b) drifts parallel to schistosity (ψ = 0°) in a rock mass not strongly affected by schistosity

Seismic clusters aligned along disturbed schistosity (north-northeast portion of the stereonet) mainly occur for development blasting located outside a shear corridor. Therefore a good fit exists between the observed structures in the studied sector and the seismic response orientations because the disturbed schistosity planes were not observed in shear corridors but in their surroundings.

When the seismic responses are associated with a weak shear movement along the planes of the undisturbed or disturbed schistosity (the north or north-northeast portion of the stereonet), their maximum seismic moment is less than those related to stress-induced horizontal fracturing, which is expected. It must also be considered that the quantification of the orientation of the seismic response is only possible when five or more events define it; a response generated by movement along a minor structure such as a joint is expected to be less significant than a response related to the shear movement associated with a major structure.

5 Conclusion

This paper contributes to improving our understanding of seismic response to development blasting in a deep underground mine by investigating seismic response orientation and the intensity of the relationship with the stress regime and large-scale structures. A plane-fitting algorithm using PCA allowed the orientation measurements of 228 seismic responses to blast development for a deep sector of the LaRonde mine. The poles of the seismic responses are showing that the alignment of the seismic responses is not random. The main contributions offered by this study are:

- Only few seismic response are oriented along interpreted shear corridors.
- Most of the responses were aligned along the direction of the two major principal stresses (σ_1 and σ_2) at the mine, which are horizontal.
- Most high seismic moment responses have resulted in a sub-horizontal PCA plane, and these occur mainly following development blasts of drifts excavated parallel to schistosity.
- The sub-horizontal seismic responses seemed to happen with a buckling-like mechanism, mainly occurring with blasts in drifts parallel to the schistosity.
- Other clusters of oriented seismic responses seemed to occur by deconfinement of disturbed or undisturbed schistosity planes.

Acknowledgement

The authors would like to acknowledge the excellent collaboration with LaRonde mine (Agnico Eagle Ltd) personnel at the site. This project was made possible by the financial support of Fonds de Recherche du Québec – Nature et technologies.

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