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Geoseismic strategy for monitoring seismic hazard at Westwood mine

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Abstract

The Westwood mine features a complex geological environment characterised by a high contrast in geological units of varying competence, faults with different orientations and deformation corridors. This complexity presents significant challenges for mining operations, which results in seismic activity being a well-known major issue. Since the start of operations in 2013 several major seismic events have occurred, leading to health, safety and operational problems, and resulting in the complete shutdown of operations in 2020. To ensure the safe and efficient resumption of activities at the Westwood mine, a geoseismic monitoring strategy has been implemented. This strategy includes a geoseismic characterisation of the rock mass of the mine site, enhancement of the seismic system, regular monitoring of seismicity and the implementation of various seismic analysis methods. Through this strategy several aspects of seismicity are closely monitored, including identification of geological contexts related to major events/rockbursts, assessment of seismic event quality, calculation of the current seismic hazard, monitoring of abnormal seismic activity, seismic response to blasting analysis, assessment of the re-entry protocol and stress monitoring using the seismic response to blasts. Through this geoseismic strategy a better understanding of the seismic behaviour of the Westwood mine has been achieved. Currently some aspects of the seismicity can be anticipated, such as high seismic hazard locations, the probable maximum event magnitude to occur at a particular location and its probability of occurrence. Based on this information an exclusion protocol is implemented during blasting to reduce worker exposure and this information is used as a guideline in the design and reinforcement of the ground support system.

Keywords: *mine seismology, seismic hazard, seismic analysis, seismic hazard map*

1 Introduction

In underground mines with seismic activity, seismic risk can be classified as extreme as the most severe consequences can result in multiple fatalities and extended periods of mine shutdown, or even permanent closure in the worst-case scenario (Potvin et al. 2019). Proactive risk management as currently implemented at the Westwood mine is therefore paramount for mines operating in seismic conditions. The Westwood mine is situated approximately 40 km east of the town of Rouyn-Noranda in the Doyon-Bousquet-LaRonde mining district of Quebec, Canada. The geological setting at the mine is complex, marked by a stark contrast in resistance between geological formations, faults spanning in various orientations (east–west, north–south and oblique) and a deformation corridor. This intricate landscape poses considerable challenges during mining activities, with seismic activity emerging as a prominent concern. Since operations began in 2013 numerous significant seismic events have occurred, causing serious safety concerns and disruption to operations, and eventually leading to a complete cessation of production activities for several months in 2020.

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To address this risk a geotechnical algorithm based on a multi-faceted approach is employed to characterise the behaviour of the rock mass and determine the necessary risk mitigation measures (Figure 1). This approach involves the evaluation of multiple aspects to anticipate the spatial and temporal behaviour of the rock mass effectively. Various mitigation measures can then be implemented to reduce the geomechanical risk, particularly seismic risk. However, understanding mine seismic hazard requires in-depth seismic analyses. Indeed, future seismicity in a mine is closely linked to past seismicity (Hudyma 2010) to a certain extent. Thus the best opportunity for identifying mine seismic hazard lies in systematic back-analyses and the interpretation of seismic data. It is undeniable that the more seismic analyses we conduct, the better we understand the local seismic response associated with mining activities. Additionally, it is recommended that every seismically active mine should have a seismic risk management plan in place (Potvin et al. 2019). Hence the relevance of this article, which summarises the implementation of a seismic risk management plan at the Westwood mine.

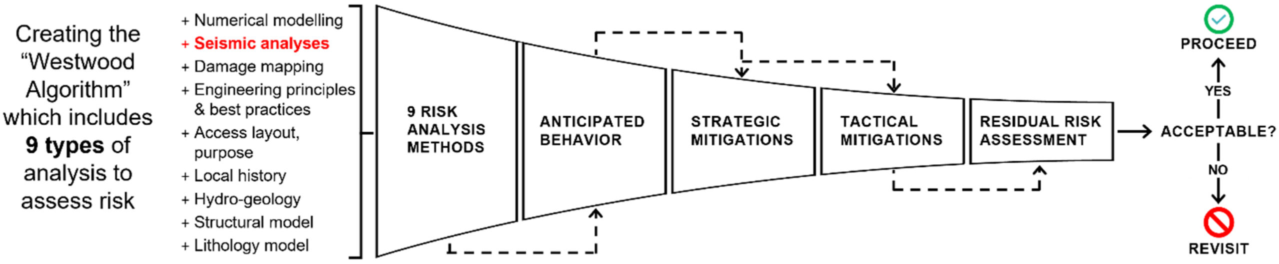

Figure 1 Geotechnical risk assessment algorithm of the Westwood mine

This seismic risk management plan is called a geoseismic strategy because it is based on the characterisation of geological mining activities/geometry and seismic data. A combined geomechanical characterisation and seismic response analysis are conducted to identify rock mass conditions that correlate with seismicity. With knowledge of the geomechanical conditions associated with seismicity, a pre-mining seismic risk hazard map (HazMap) has been developed on a mine scale. This HazMap classifies different areas of the mine according to their potential to generate low seismic responses and high seismic responses with low magnitude, and their susceptibility to generate higher magnitude events. In addition to this HazMap, a suite of seismic analysis methods has been developed and implemented to track seismic behaviour and anticipate associated risks. This strategy is entirely dedicated to seismic risk management in which: several aspects of seismicity are closely monitored, including the quality of the seismic data; areas of high seismic potential are identified; seismic hazard is calculated; the seismic response of structures is monitored; abnormal seismicity is identified and evaluated; the seismic response to blasting to define exclusion zones and times is analysed; and stress is monitored using seismic response to blasts. Abnormal seismicity is defined in this strategy as the presence of unexpected moment magnitude (MW) of seismic events in a low-potential seismic area, as well as the presence of a cluster of events with no known triggers. Figure 2 details the structure of this strategy and the following sections explain each aspect.

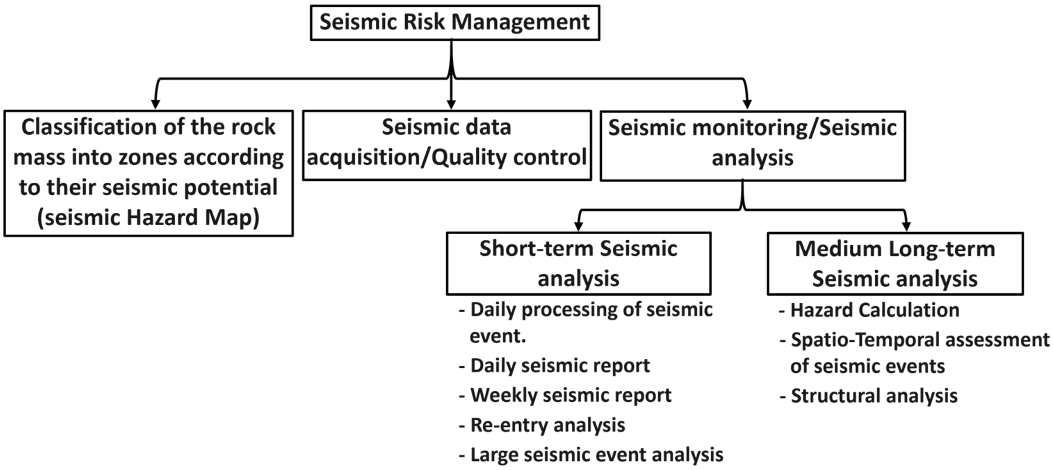

Figure 2 **Structure of the geoseismic strategy at the Westwood mine**

2 Seismic hazard map

A better understanding of seismic response requires a more thorough geoseismic characterisation of the rock mass. According to Hudyma & Potvin (2004), seismicity in mines is influenced by the level of induced stress, local geology and mining activity.

The geology of the Westwood mine is recognised as being highly complex and variable. The geology is generally characterised by the presence of seven large lithologies of variable thickness primarily oriented east–west. These units are offset by the Bousquet Fault, a sub-vertical structure oriented northeast–southwest. In addition to this major fault, several other local faults are present and are classified into three groups of faults according to their orientations: east–west, oblique and north–south (Figure 3).

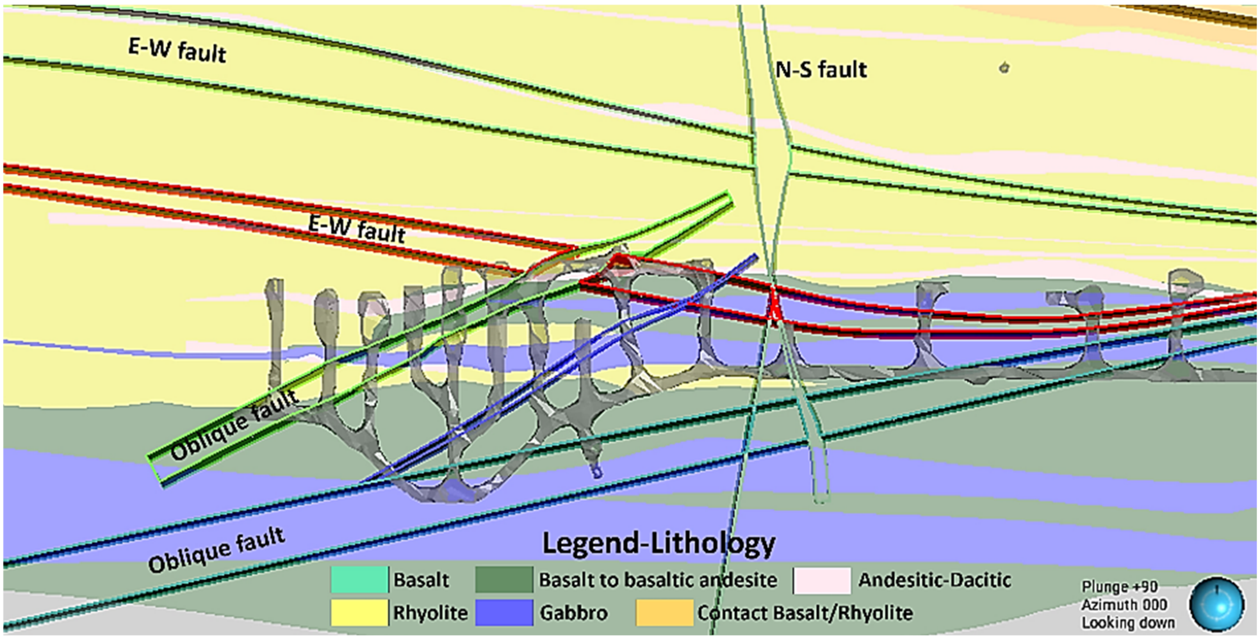

Figure 3 **Overview of the Westwood mine geology (plan view of level 132-03) showing alternation of competent dykes with less competent units intersected by faults of different orientations**

The lithologies at the Westwood mine that are primarily associated with seismicity are the basalt/rhyolite contact and dykes, including gabbro, andesite-dacite and basaltic andesite. The seismic potential of these units is strongly influenced by the presence of faults. Moreover, the configuration of these faults represents a critical factor that greatly increases the seismic potential to an extreme level. Figure 4 shows the spatial distribution of seismic events from two different areas, namely level 104-00 of the central zone (Figures 4a and c) and level 132-03 of the western area (Figures 4b and d).

In Figures 4a and b it can be observed that the basalt/rhyolite contact and dykes generate high seismic responses of low magnitude. However seismic events of high MW are mostly localised in zones where structures meet, such as the intersection of oblique and east–west faults, of north–south/oblique/east–west faults within those problematic units, and of oblique faults and dykes (Figure 4c and d, seismic events of MW ≥ –0.5).

Based on this analysis the mine areas have been classified according to their current seismic potentials (Table 1). The seismic potential of an area refers to its predisposition to generate seismic events. This predisposition depends on the presence of seismic structures, the arrangement of these structures (such as intersections between them) and the number of structures.

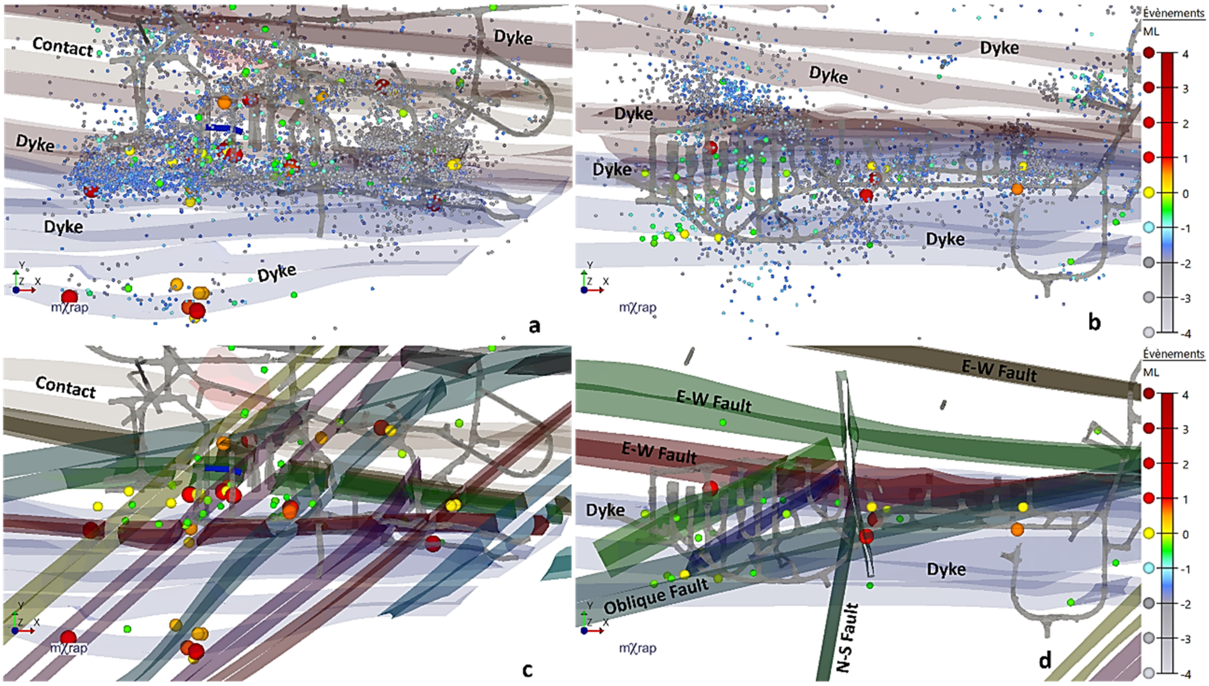

Figure 4 Overview of the geoseismic context of the Westwood mine: (a) Level 104-00, spatial distribution of seismic events versus lithology; (b) Level 132-03, spatial distribution of seismic events versus lithology; (c) Level 104-00, spatial distribution of seismic events versus lithology and faults; (d) Level 132-03, spatial distribution of seismic events versus lithology and faults

Table 1 Classification of mine areas according to their seismic potential (classification A)

Seismic potential	Risk factors	Seismic behaviour
High	S–N fault + oblique fault + E–W fault + dyke of gabbro/andesite S–N fault + oblique fault + E–W fault + contact basalt/rhyolite	Moderate to low seismic response with large events
Moderate	Oblique fault + E–W fault + dyke of gabbro/andesite Oblique fault + E–W fault + contact basalt/rhyolite	Moderate to high seismic response with moderate and large magnitude
Low	E–W fault + dyke of gabbro/andesite E–W fault + contact basalt/rhyolite	High seismic response with low magnitude

Currently the seismic potential of each area of the mine is determined based on factors that control seismicity (Figure 4). The more an area is characterised by the presence of multiple risk factors favouring seismicity the higher its seismic potential, and vice versa. Using this information, a seismic HazMap has been established at the mine scale (Figure 5). Furthermore, the exposure factor for personnel or permanent infrastructure specifically affects the classification of an area. Thus all areas near a ramp or main crosscut are classified accordingly.

Additionally, another classification based on the seismicity level has been carried out. This classification reflects the effective seismic potential of the areas. It is assessed based on the ML recorded and the maximum number of seismic events generated by blasting. These two parameters can vary over time depending on the level of mining activity. The higher they are the more significant the seismicity level. Table 2 provides a summary of this classification.

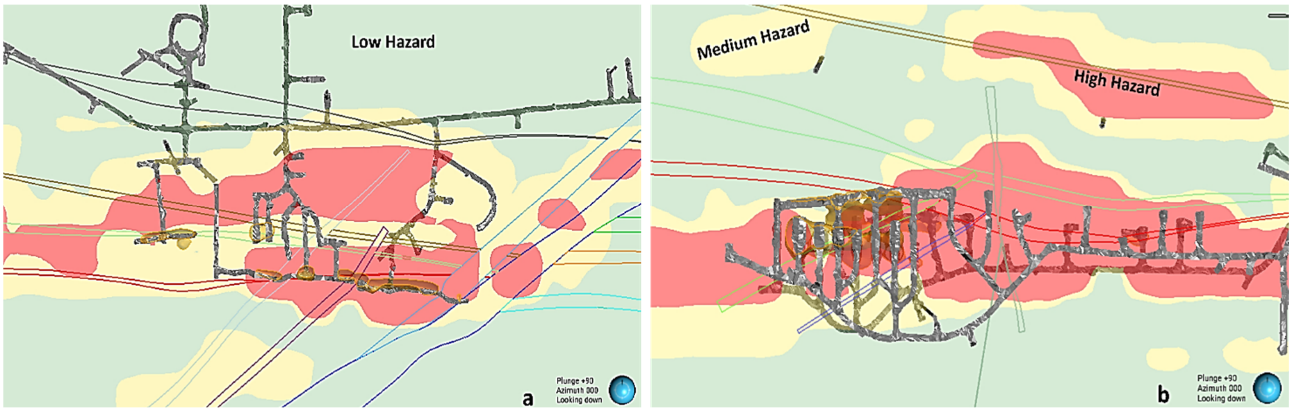

Figure 5 **Seismic hazard map (HazMap) where a red represents high hazard, yellow corresponds to medium hazard, and green to a low hazard area: (a) HazMap of level 104-00 of the mine central area; (b) HazMap of level 132-03 of the west mine area**

Table 2 **Classification of mine areas based on their levels of seismicity (classification B)**

Level of seismicity	Risk factors
Very high	Maximum magnitude ≥ 1.0 Events count by blasting ≥ 100
High	Maximum magnitude ≥ 0.0 Events count by blasting ≥ 50
Moderate	Maximum magnitude ≥ –0.5 Events count by blasting ≥ 20
Low	Maximum magnitude ≤ –0.5 Events count by blasting ≤ 20

According to these various classifications, suitable ground control measures are implemented to mitigate the anticipated seismic risk. Using the area potential classification (classification A), future developments are adequately designed and planned along with ground support system requirements. Specific measures are also implemented, such as: establishing exclusion zones and times; limiting activity, i.e. no production blasting at the same time as development blasting; installation of more robust face support; employing remote-controlled equipment; and utilising armoured-cabin equipment. These measures are updated based on the observed seismicity level (classification B). For example, exclusion measures may increase or decrease, there may be other limitations on the number of blasts per shift, seismic checks will be completed with mandatory written confirmation from a geotechnical engineer before re-entry into excluded sectors is allowed, and de-stress blasting may be used. Additionally, various seismic monitoring and analysis are conducted to monitor seismicity, particularly for high seismicity areas. These analyses are detailed in the following sections.

3 Seismic data acquisition/quality control

The conclusions which can be drawn from any seismic analysis are only reliable if they are based on good quality seismic data (Morkel et al. 2015). Indeed if the data quality is poor, or if the recording is short and/or the number of seismic events involved in the analysis is limited, the relevance of the analysis may be affected (Hudyma 2010). The quality of events depends primarily on the sensitivity of the seismic system acquisition and processing. The sensitivity of a seismic system is evaluated through the detectability of seismic events, which refers to the system's ability to capture low magnitude events and the precision of its identified locations. This sensitivity is closely linked to the density of the seismic sensors array, the type of sensors, installation quality and the velocity model used. To ensure good seismic sensibility it is essential to have enough seismic sensors installed at reasonable distances to ensure proper 3D coverage of the volume of interest. Thus to ensure adequate coverage at the Westwood mine a standard has been implemented based on recommendations from the literature. The entire mine is covered as follows: Minimum detection capability of MW ≤ –2.0 with a location error margin less than 10 m. The mXrap system design application is used to plan the installation of seismic sensors with a ratio of three uniaxial sensors to one triaxial sensor (Collins & Hosseini 2013). This application allows for evaluation of the number of seismic sensors and the maximum distance required between them to achieve the desired minimum coverage at a location. Additionally, two strong ground motion (SGM) sensors are installed to improve calculated source parameters of significant seismic events.

Three levels of event processing are implemented. First is the automated onsite procedure, which is an automatic processing of triggers by an ESG acquisition computer. Then there is a remote analytical service (ESG RPS) which is performed using advanced automatic and interactive processing algorithms. An expert can assist in the processing of events with higher location error and for tagging assessment as well as large magnitude event analysis. Finally, daily manual processing and verification is also carried out onsite by one of the site geotechnical engineers.

During the seismic analyses an evaluation of seismic data quality is carried out. Seismic data quality monitoring is performed though the seismic event data quality application of mXrap (Morkel et al. 2015; Morkel & Wesseloo 2017). It is also conducted using a simple technique developed at the mine which involves evaluating the sensitivity of the seismic system and processing performance. The parameters evaluated include the minimum MW recorded, the location error associated with events and the number of sensors that captured the seismic event. For example, in Figure 6a the sensitivity of the seismic system in this area of the mine is very good, with a minimum magnitude of MW–3.04. Seismic coverage and accuracy are also very good, with an average of 14 sensors (Figure 6b) and a location error less than 10 m for most seismic events (Figure 6c).

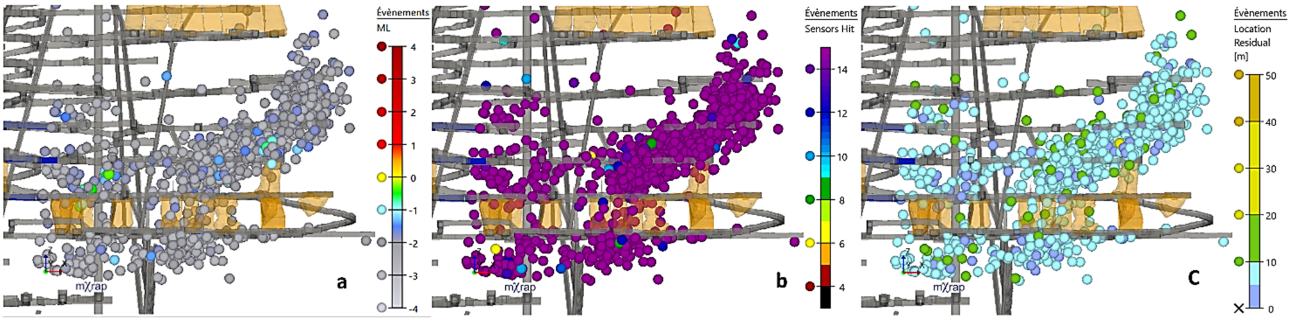

Figure 6 Quality of seismic events assessment: (a) Sensitivity of the seismic system assessment; (b) Seismic coverage assessment; (c) Location error assessment

4 Seismic analysis

In addition to the geoseismic characterisation of the rock mass, continuous and adequate seismic monitoring is necessary to improve understanding of the seismic behaviour in order to anticipate seismic risks as effectively as possible. Several methods for analysing seismic data are available in the published literature. Although these methods are proven and accepted in many mines they all have limitations. Probability calculations provide an estimate of the maximum magnitude that could occur in a mining area although it is impossible to predict when this event might occur. The main challenge is that these seismic events remain unpredictable. Therefore, for effective seismic monitoring, all existing methods and techniques should be considered when analysing and interpreting the seismic behaviour of a mine. It is worth noting that the mXrap software offers several of these seismic analysis methods (Harris & Wesseloo 2015).

During the seismic analyses it is crucial to know what and how to analyse. It is important to know which source parameters are significant to the analysis and the basic principles for using these parameters, as well as the time interval, to obtain a reliable trend of the evaluated parameter. It also necessary to look for trends and cause-and-effect relationships in the data and compare the seismic response of the rock mass to mining activities. In this regard a set of analysis methods has been implemented at the Westwood mine over the past three years to monitor seismicity. The types of seismic analyses implemented in this strategy are of two types, namely short-term and medium- to long-term (Figure 2).

4.1 Short-term seismic analyses

Short-term seismic analyses involve managing seismic risk over a short period. These analyses consist of evaluating the quality of seismic data and assessing the trend of the seismic response to mining activities. These analyses occur over varying time frames ranging from six hours to one week of seismic response (daily and weekly seismicity). These analyses allow for close monitoring of: the quality of the seismic data and seismic system health; seismic activity in seismic areas (trends and clustering of events); the probability of a major seismic event (seismic hazard); and re-entry protocol analysis.

4.1.1 Daily seismicity

The daily seismic report represents the first tool for seismic monitoring. It is a technique developed by IGM Geotechnical which involves documenting mining activities and their related seismic response over the past 24 hours. The important elements monitored in this report incorporate seismic system health, including: verifying the number of good seismic sensors and the quality of the automatic seismic processing; analysing seismic behaviour, i.e. checking if seismicity is normal in different areas; verifying if the seismic response to blasts corresponds to what is anticipated (as presented in Tables 1 and 2); looking for the presence of clusters or major seismic events and, if found, identifying the possible triggers and whether there is a notable change in the daily activity rate without any particular reason, i.e. blasts, stope not backfilled; and installation of ground support in a seismic area that would warrant special attention.

During this daily analysis any concerns related to seismicity are immediately discussed with the ground control team.

4.1.2 Weekly seismicity

The weekly seismic analysis constitutes the second seismic monitoring tool of this strategy. It is a technique implemented by IGM Geotechnical, and enhanced by the Westwood mine ground control team, that involves analysing seismic data from a week to obtain a short-term view of seismic risk. The elements monitored in this analysis are detailed in the following section.

4.1.2.1 Seismic hazard state

This consists of the evaluation of the seismic hazard variation. In this evaluation seismic hazard is calculated in terms of the probability (P) of occurrence of a given magnitude (Wesseloo 2018). To obtain an accurate understanding of this variation, analysis periods of three, six and 12 months are used. This probability is assessed at the mine scale within a 50 m radius around an excavation and is projected onto the drifts to provide a 3D view (Figure 7a). An evaluation of this seismic hazard is also conducted at the area scale over its 12-month history, with results presented in graphical form (Figure 7b). In this Figure, an increase in P (ML > 2) is observable from September to December 2023 as well as in March 2024. During these periods some significant seismic events were recorded in these areas (Figure 8). Furthermore, during this analysis any increase in seismic hazard is reviewed. The increase in this hazard is often related to a change in the seismic activity rates, which provides insights about the rate and/or area of rock mass deformation.

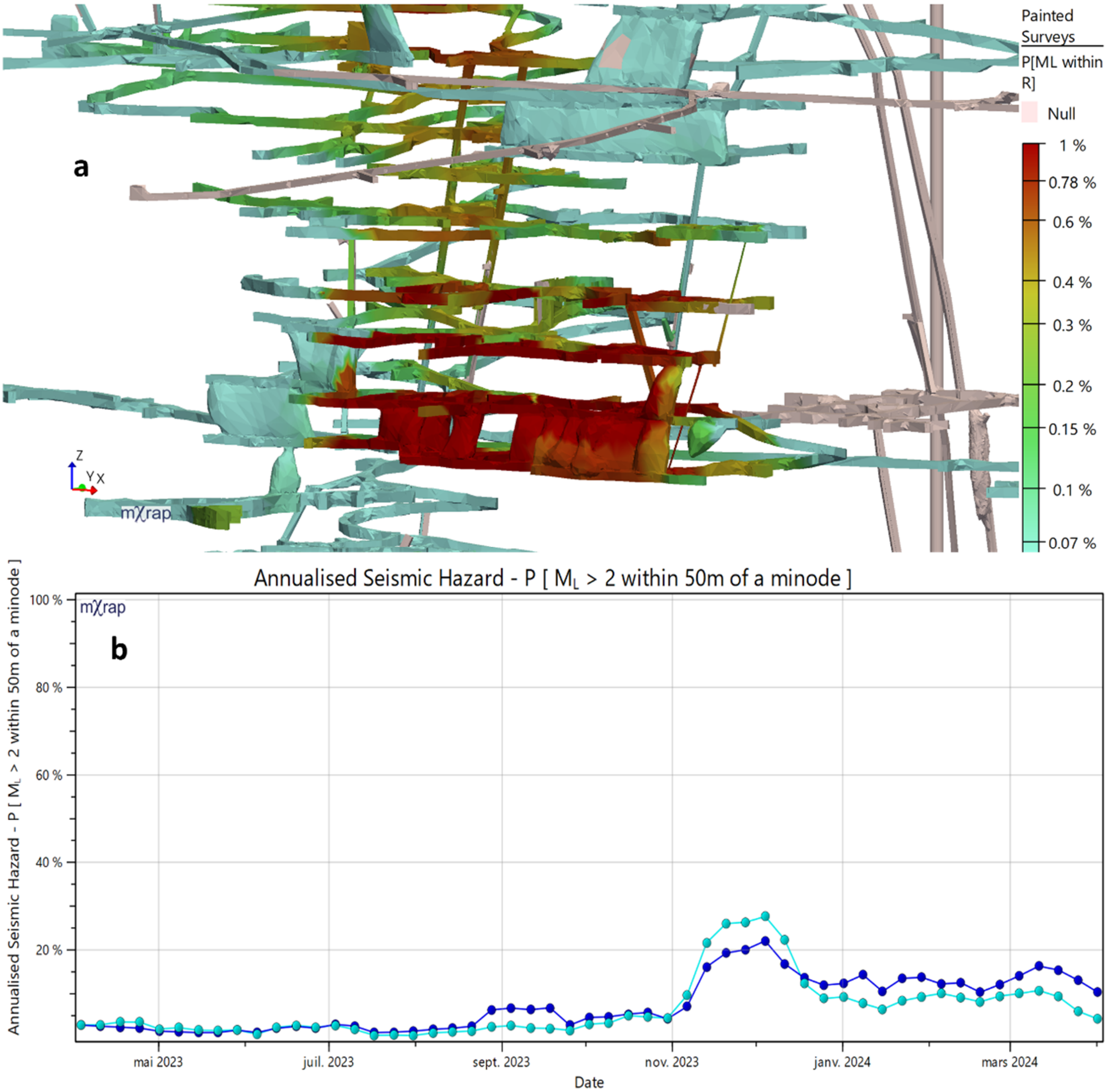

Figure 7 **Seismic hazard calculation: (a) Probability of having an ML > 2 considering the six-month event rate and a b-value calculated over 10 years; (b) Probability of having an ML > 2 at the zone scale over 12 months considering the one-month seismic event rate history and a b-value calculated over 10 years**

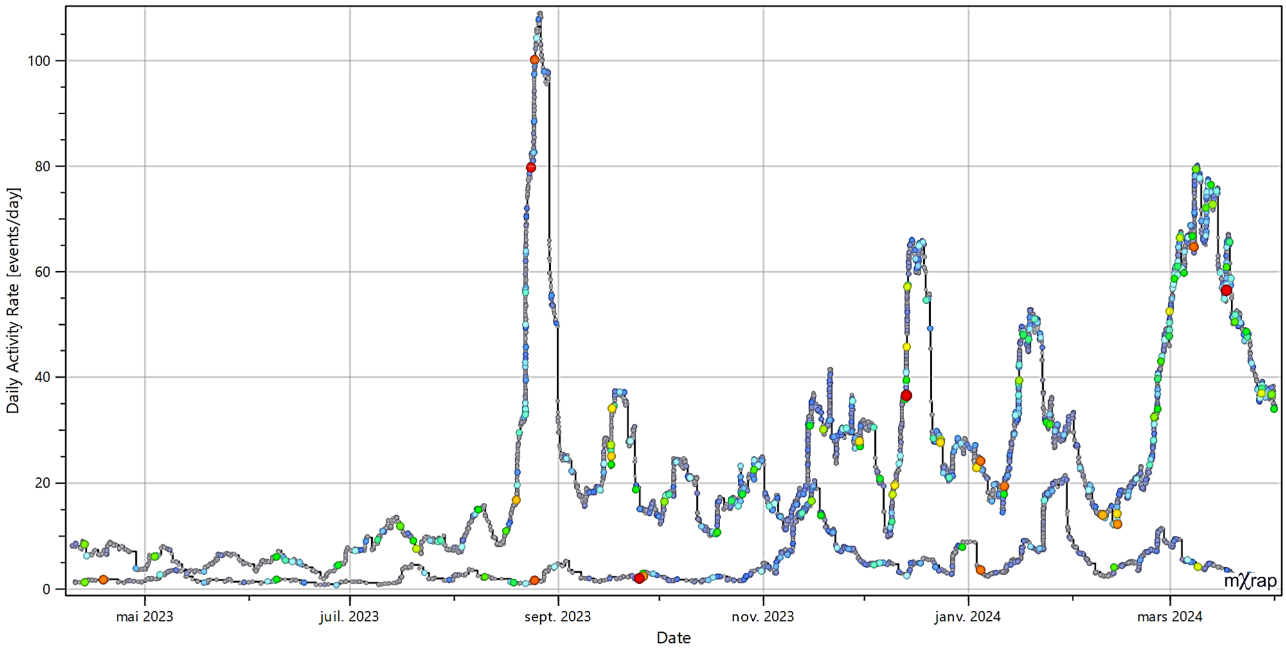

Figure 8 **Daily seismic activity rates for the different zones of the mine over a 12-month historical period**

4.1.2.2 Seismic activity rate of areas

The seismic activity rate represents the number of seismic events per day and is sometimes used as a relative indicator of seismic hazard (Figure 8). It allows identification of the normal seismicity level compared to an abnormal seismicity level. The activity rate is evaluated per area, given that seismic potential, seismicity level and mining activity rates can vary from one area to another. To obtain a good understanding of this activity rate, a 12-month period of activities is assessed. Any increase in seismic activity rate is investigated.

4.1.2.3 Spatial and temporal arrangement of seismic response

The spatial and temporal arrangement of seismic events is used to evaluate the source of seismic events (i.e. triggered by structures [Figure 9a] or blasting, or related to stress adjustment [Figure 9b]). The magnitude-time graph is one of the tools used to provide an overview of occurred seismicity, which can be a proxy for seismic hazard. This graph shows a cumulative curve (blue curve, Figure 9b) and a chronological distribution of seismic events. The slope of this curve represents the seismic event rate, indicating how it evolves over time. The step-like behaviour of the curve is an indicator of a strong response of the rock mass to blasting. A constant slope of the curve indicates that seismicity is not directly triggered by blasting, which is often the case with seismic behaviour controlled by structures. Changes in the slope are considered an indicator of a change in the rate of the rock mass rupture process (Hudyma 2010). Regarding the chronology of events, it provides an indication of whether the most significant events are directly triggered by blasting. For structurally controlled seismicity, the most significant events do not necessarily occur at the same time as most of the events. Furthermore, an increase in the maximum magnitude of events may be an indicator that the failure process is worsening or that the failure volume is increasing (Hudyma 2010).

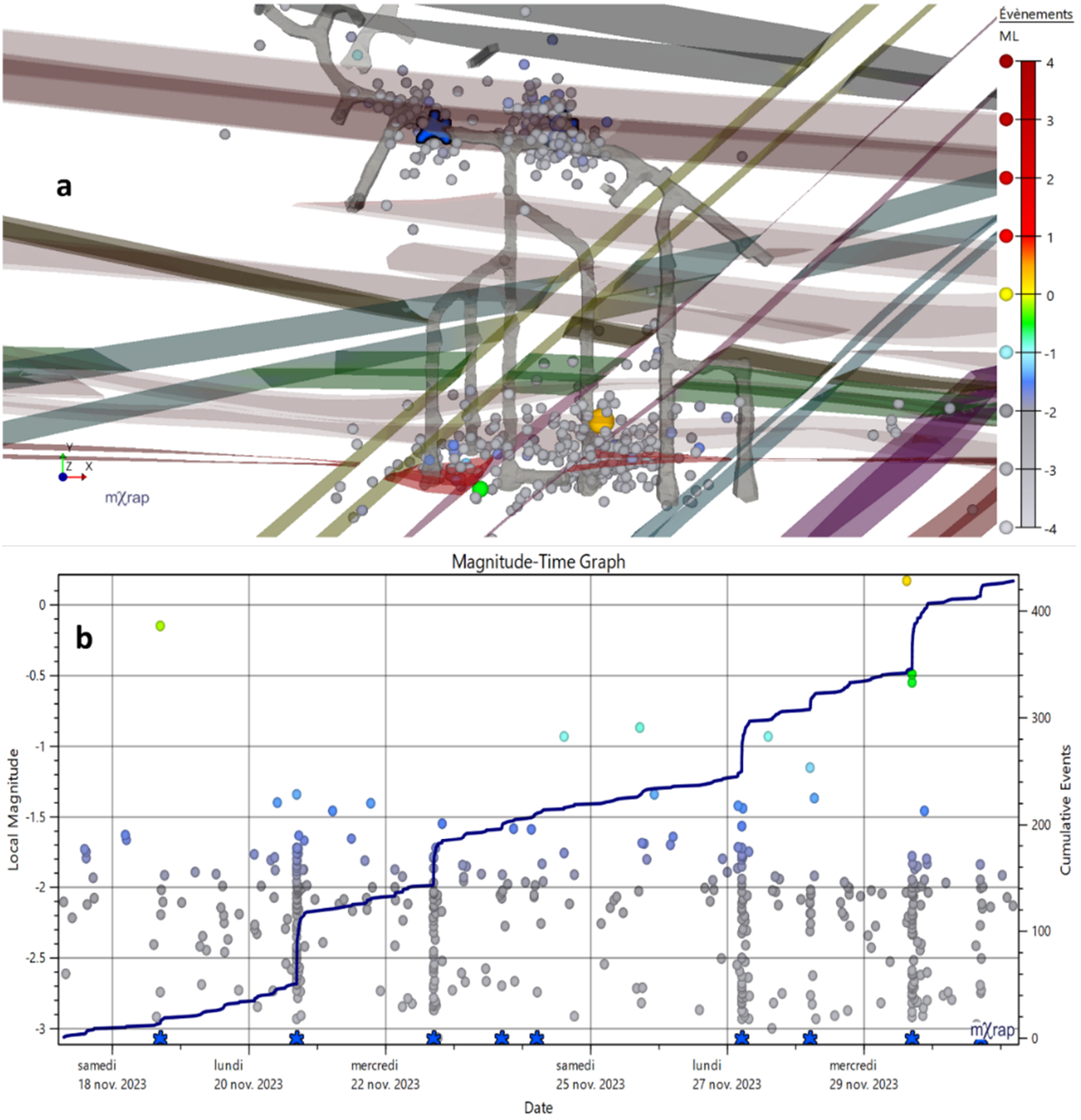

Figure 9 **Spatial and temporal arrangement of the seismic response on level 132-10: (a) Arrangement of seismic events versus structures (faults and dykes); (b) Magnitude-time graph of the seismic response**

4.1.3 Re-entry protocol analysis

Seismic monitoring of blasts aims to manage exposure to seismic risk. The goal is to reduce the risk by withdrawing personnel from work areas during periods of high risk, such as after blasting and periods of intense seismic activity. In practice, the re-entry protocol assesses the current seismic hazard, managing seismic risks based on how seismicity is induced (Morkel & Rossi-Rivera 2017). When seismicity is closely linked to blasting, most seismic risks can be mitigated by using short exclusion periods. But if seismic hazard does not vary over time there is no justification for temporary exclusion since it is not time-sensitive. The effectiveness of a re-entry protocol depends on the average exclusion duration and the percentage of major events occurring during this period (Morkel & Rossi-Rivera 2017; Vallejos & McKinnon 2010, 2011). This is why three distinct protocol types are used for determining when and which area to exclude, and when to reintegrate an area.

In this strategy the implementation of a re-entry protocol is performed using the short-term response analysis application (Harris & Wesseloo 2015). Using this application, a back-analysis was conducted to define the re-entry protocol of the Westwood mine. This re-entry protocol provides an exclusion time ranging between 3, 6, 12, 18 and 24 hours, according to the seismic response of the area and its seismic potential (refer to Tables 1 and 2). The exclusion radius ranges from 50 to 200 m, according to seismic response and the geometry of the excavation.

These ranges were defined based on previous seismic response, which also aligns with the seismic potential of the different areas (Table 1). They may vary under certain conditions, such as the opening of a new area and blasting of a higher tonnage than usual. In areas with high seismic potential and response, or when a major event is recorded during a blast, a re-entry analysis is conducted before an excluded area is reopened. During this analysis, re-entry is considered favourable when 50% of the seismic response is reached, when background seismicity is reached or when it returns to the tolerated seismic risk. Seismic risk is considered acceptable when the seismic response or background seismicity within a radius of 15 to 25 m is less than five events every two hours, and has a magnitude less than zero. When a major seismic event occurs following a blast, a ground movement analysis (Harris & Wesseloo 2015) is conducted to assess the probability of excavation damage and to delineate potentially affected areas for inspection before proceeding with the reopening of the excluded area. When the probability of damage is high, specific measures can be added to proceed with the reopening.

4.1.4 Post-large seismic event analysis

The occurrence of a major seismic event can have significant consequences for the mine. During such an event several actions must be quickly taken to ensure the safety of all personnel working at the mine, particularly underground. Managing such a situation requires a management plan. At the Westwood mine, an urgent response plan which is heavily based on the seismic trigger action response plan (TARP) has been implemented. The seismic TARP is a tool that details the steps to better handle a declared seismic event and make informed decisions in response to the situation. When a seismic event occurs the seismic TARP addresses the following: determination of the location and magnitude of the seismic event; identification as to whether the event is in a closed or active area; evaluation of the need for exclusion; definition of the radius of the exclusion zone, as well as the exclusion period if necessary; and the necessity of performing post-large seismic event analysis.

Post-major seismic event analysis involves assessing the potential for excavation damage, understanding the mechanism behind the event and monitoring the seismic response of the major event. This information is useful when excluding a level, area or the entire mine. In extreme cases this information can be used by the rescue team by providing guidance on seismic response migration and high-risk areas.

4.1.4.1 Excavation damage potential due to large seismic event

The potential damage of the excavation is defined based on the degree of shaking caused by a seismic event, which is assessed using peak particle velocity (PPV, m/s) through the mXrap software. Low vibration (low PPV) at a location of interest indicates a lower level of stresses and dynamic deformations caused by rock mass vibrations and vice versa (Dubiński & Mutke 2012). Figure 10 provides examples of PPV assessment following a major seismic event. During such analysis it is necessary to have information on the quality of ground support in the area affected by the event. Adequate ground support could significantly mitigate the anticipated potential damage indicated by the PPV. For example, the PPV associated with the cases in Figure 10 inferred a high hazard level for damage (0.51 m/s for Figure 10a and 0.69 m/s for Figure 10b). However minor tensile slabbing, small rock shard ejections and minor cracking of the shotcrete were the only damages observed. Furthermore, the PPV can be influenced by certain factors such as the location of the seismic event, i.e. the identification of the P-waves and S-waves, its proximity to the excavations, and other seismic parameters where their interpretations must be done diligently.

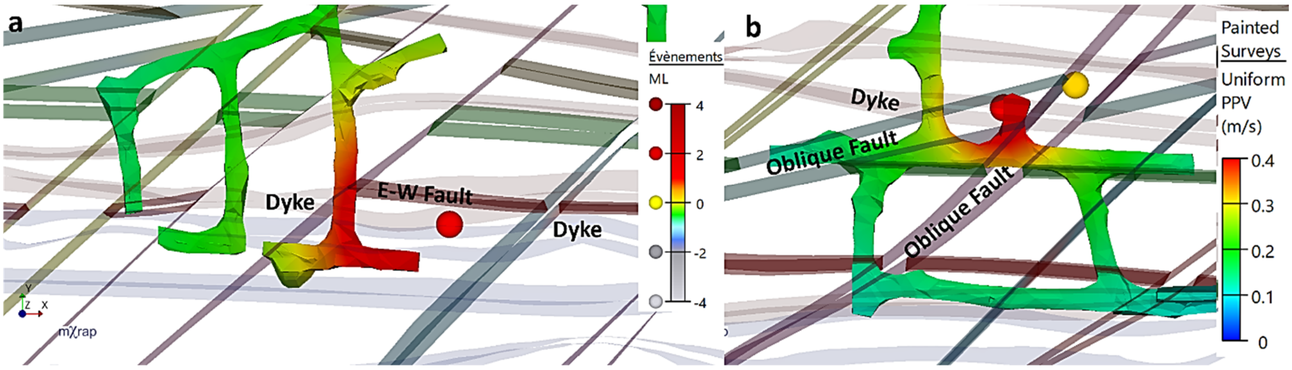

Figure 10 Peak particle velocity versus drift/structures following a large seismic event: (a) Level 132-09 of the mine; (b) Level 157-00 of the mine

4.1.4.2 Source mechanism

In the characterisation of a major seismic event the source mechanism is used to determine the potential triggers of that event. A fracturing mechanism on the excavation walls is generally linked to mining operations while a mechanism associated with major geological discontinuities is often independent of mining operations (Hudyma 2010). As a first pass, an idea can be found about the potential source mechanism based on the P-waves' and S-waves' energy ratio of a seismic event. Events associated with fault slips frequently have Es:Ep energy ratios greater than 10, which indicates that shearing is involved. S-wave and P-wave energy ratios ranging from one to three can be an indication of stress fracturing, tensile failure and volumetric stress changes (Morkel et al. 2019). Additionally, an assessment of the spatial disposition of the event relative to structures is used to validate the interpretation obtained from the Es:Ep ratio. This validation is necessary due to a potential inconsistency of the Es:Ep ratio (Morkel et al. 2019). For example, in Figure 10a, the Es:Ep ratio of 12 inferred a fault slip, which aligned with the event occurring in an oblique fault. The Es:Ep ratio of 6.2 for the event in Figure 10b inferred a mixed rupture. This also corresponded to the geological context of the event location near the contact of two dykes. This interpretation technique is relatively straightforward and provides a first pass understanding of the source mechanism of a seismic event. However, for larger events, more in-depth analyses are conducted for further validation such as the moment tensor inversion analysis.

4.1.4.3 Post-large event risk analysis

This analysis involves the continuous assessment of the seismic response. This helps determine whether post-major event seismicity increases or decreases over time. A decrease in seismic response is necessary to consider re-entry into the area. The exclusion protocol for the affected area is applied and updated in case of increased seismicity. The graphs in Figure 11 show the cumulative seismic events before and after the concerned seismic event and are used for seismic monitoring. They are also used at the beginning of the investigation. The pre-event portion of the graph provides an overview of the seismic behaviour of the sector, including the number of blasts and the sector's seismic behaviour. The post-event part of the graph is used to evaluate the seismic response to the major event to make an informed decision regarding the re-entry of the excluded sector/area. The re-entry is considered when the slope of the curves on these graphs becomes gentler, indicating attainment of the background seismicity in the area.

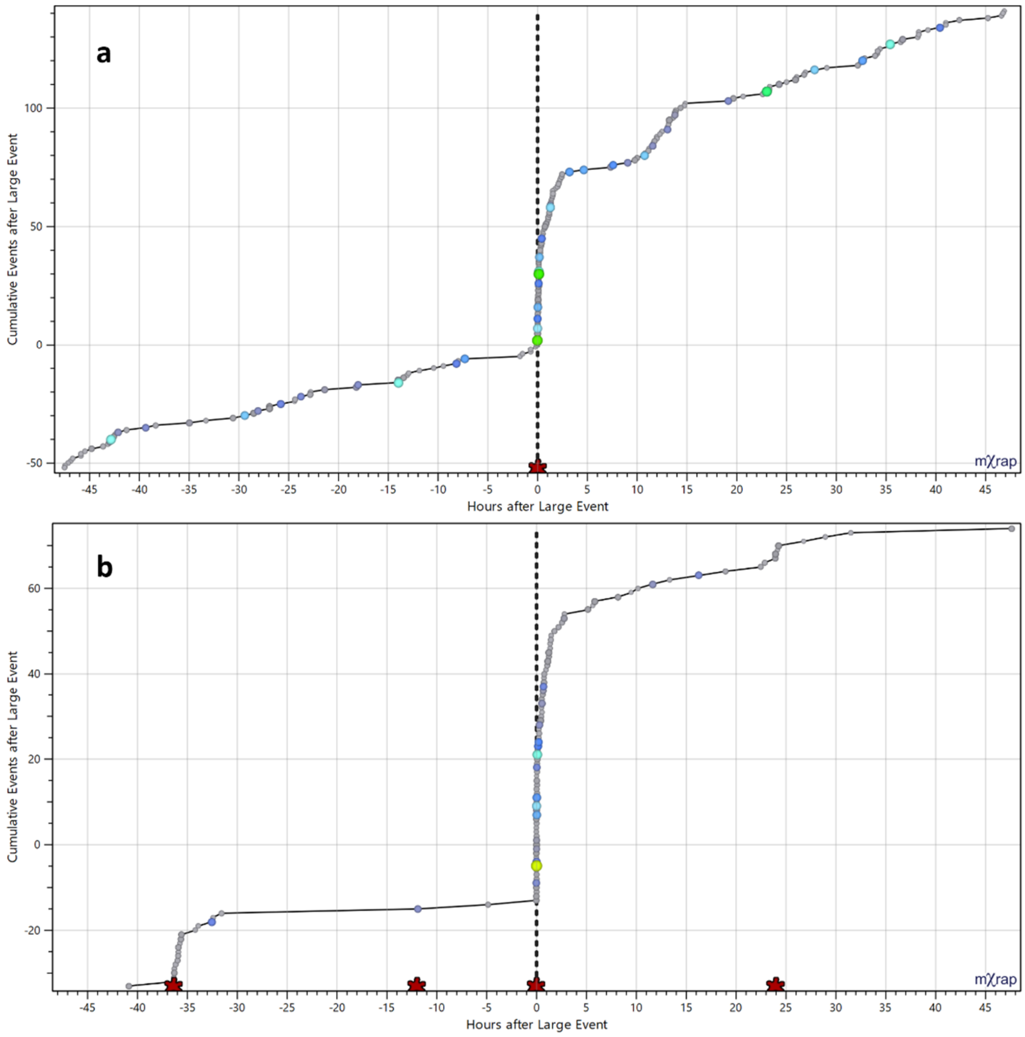

Figure 11 Cumulative events after a large event: (a) Level 132-09 of the mine; (b) Level 157-00 of the mine

4.1.4.4 Post-large seismic event back-analysis

Following each major seismic event, in-depth back-analysis is conducted to understand the seismicity of the corresponding area. Additional necessary investigations include auditing of the structural and geology models, evaluation of the seismic hazard before the major seismic event (determining if it could have been anticipated), and evaluation of the seismic behaviour of the area through the magnitude–time graph, the daily activity rate and the spatial distribution of seismic events. This helps determine if the seismicity of the area is related to mining activity and distinguishes seismicity related to structures from that which is not. These various aspects are detailed in the section on medium- to long-term seismic analyses.

4.2 Medium- to long-term seismic analysis

Medium- and long-term seismic analyses generally use the same methods as short-term analyses. However, in medium- and long-term analyses, the period analysed is at least three years, certain aspects of seismicity are examined in depth and analyses are conducted by area. During a seismic analysis prior to the reopening of an area that has been excluded for several months or years, the complete history of the area is evaluated. The following sections provide a summary of the contents of a medium- to long-term seismic analysis.

4.2.1 Seismic hazard evaluation

In these analyses, seismic hazard is assessed using three methods: b-value, the P (ML) and the maximum probable magnitude that could occur at a specific location (Hazard Isosurfaces [ISO] method, mXrap).

4.2.2 b-value (Gutenberg–Richter frequency–magnitude relation)

The Gutenberg–Richter frequency–magnitude relationship is an inverse cumulative distribution of magnitude, with the vertical axis represented on a logarithmic scale. The frequency–magnitude graph is relatively straightforward, however, its interpretation can be confusing if the various elements that compose it are not clearly understood (Wesseloo 2019). The b-value is also defined as a key element of any seismic hazard assessment. When evaluating this parameter, data within spatial filters of arbitrary size are often used. These control volumes should be defined by seismic source or seismic area as the b-value is sensitive to the spatial distribution of seismic events. That means that the b-value would be influenced by the heterogeneity of the rock mass. By grouping different sources or seismic zones with different b-values, the total calculated risk would differ from the total risk calculation based on separate sources (Wesseloo 2019). Thus in this strategy the b-value is assessed by control volume, defined using classifications in Tables 1 and 2, and evaluated over different periods (three months to three years) to validate the evaluation of temporal variation of the b-value. The minimum ML considered is –1.8. This means that the b-value is only calculated for seismic events with a magnitude of ML ≥ –1.8.

In general a high b-value equates to low risk, meaning a low maximum magnitude, while a low b-value implies high risk, indicating a high maximum magnitude.

4.2.3 P(ML) and hazard isosurfaces

The P(ML) calculation is identical to that performed in short-term analyses. However in the medium- to long-term analyses the P(ML) is calculated for different magnitudes. During this assessment the b-value is evaluated over six years and the event rate is evaluated over different periods (namely one, three, six and 12 months), aiming to find a period long enough to yield stable results yet short enough to reflect the current risk status more accurately (Wesseloo 2018). Based on the results obtained from these different periods an average risk is calculated when a significant variation in risk is observed over time.

The hazard ISO method evaluates the maximum ML likely to occur at a specific location. In other words, the ISO expresses seismic risk in two ways: the annual risk per grid, represented by the probability that an event exceeds a given ML; and the spatial distribution of risk, highlighted using risk isosurfaces based on ML (hazard ISOs). This method allows the linking of seismic risk to rock mass conditions or mining activity. For example, during operations in the mine’s eastern area, an increase in seismic hazard was observed over time (Figure 12). The data in Figure 13 and Table 3 represent the seismic hazard assessment as of 10 September 2023, and an ML = 1.2 event was recorded at this location five days later (Figure 14). During the back-analysis an increasing hazard closely coincided with a significant seismic event at the mine scale.

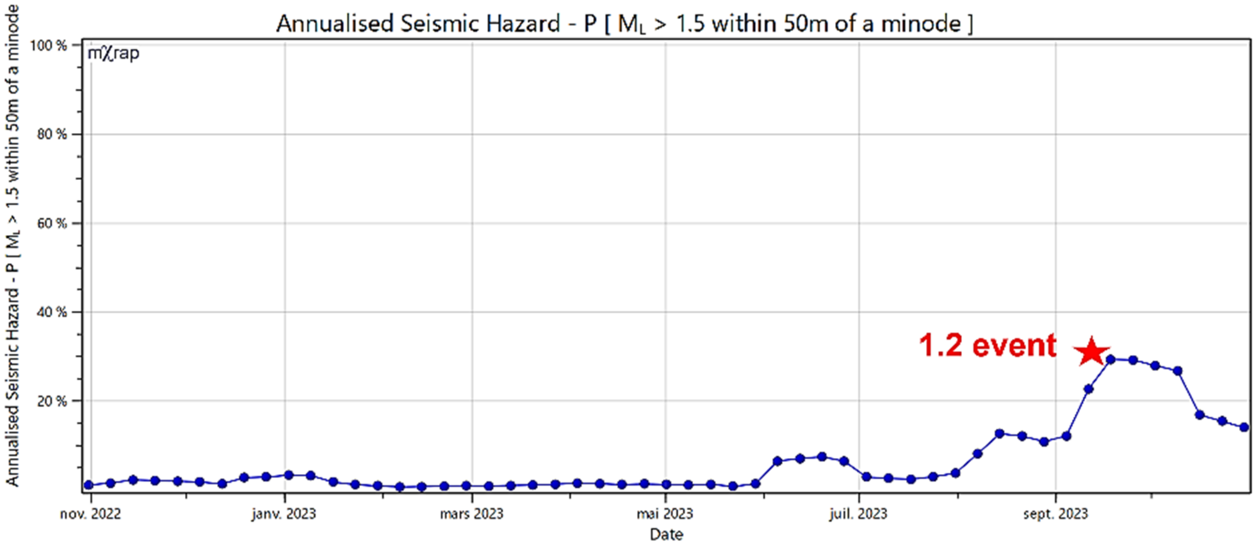

Figure 12 Annualised seismic hazard for P (ML > 1.5 within 50 m of the radius)

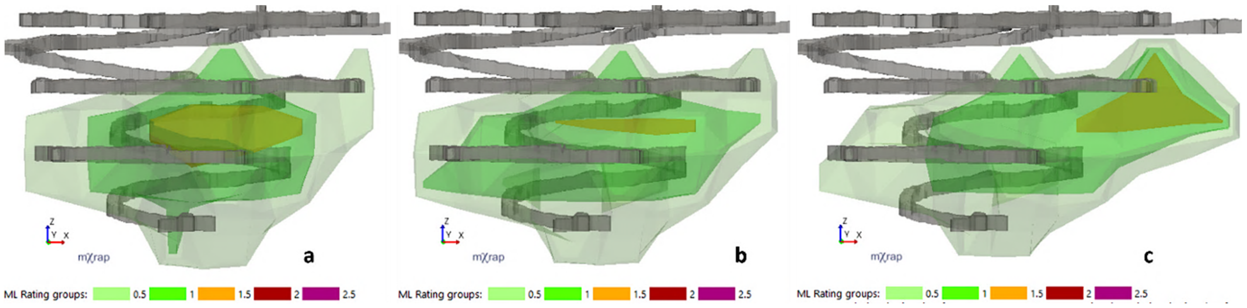

Figure 13 Hazard ISOs for different periods: (a) Three months; (b) Six months; (c) 12 months

Table 3 Seismic hazard evaluation based on b-value, P (ML) and ISO methods

Level of seismicity	Short-term (3 months)	Medium-term (6 months)	Long-term 12 months	Long-term 24 months
b-value ML_{max}	NA	NA	0.9 to 2.0	0.9 to 2.0
P (ML > 2.0)	3%	3%	3%	2%
P (ML > 1.5)	10%	9%	8%	6%
P (ML > 1.0)	26%	25%	21%	18%
P (ML > 0.5)	60%	59%	52%	51%
$ML_{max\text{-}IOSs}$	1.5	1.5	1.5	1.0

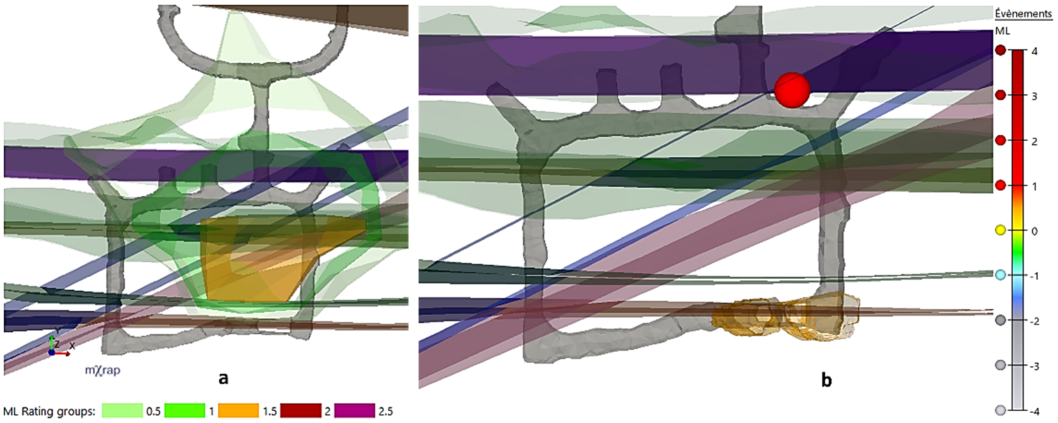

Figure 14 Hazard ISOs for level 132-06 in the eastern area of the Westwood mine: (a) Hazard ISOs versus structure; (b) Location of the 1.2 event versus structures

In seismic hazard monitoring, certain seismic parameters can indicate an increase in hazard, such as apparent stress, apparent volume and seismic moment. The grid-based analysis application is used to map the variation of these parameters. For instance, high-stress areas can be identified by apparent stress, and the deformation rate of an area is assessed using the apparent volume and seismic moment.

4.2.4 Spatial and temporal assessment of seismic events

The tools used in short-term analyses are almost identical to those used in medium- to long-term analyses. However, in medium- to long-term analyses the distribution of events is evaluated over a period ranging from three to 12 months. In addition to the magnitude-time graph and activity rate, the diurnal graph is used to develop a sense of the distribution of events based on the time at which they occurred. These help to identify whether or not the seismic response is primarily associated with blasts. Another commonly used graph is the cumulative events-stochastic declustering plot, which can be used to infer the seismic behaviour of an area.

The seismic behaviour of different areas is presented in Figure 15. The seismic response of the first area (Figure 15a) is essentially clustered, indicating a seismic response linked to blasts and low background events. However the background seismicity in the second area is nearly identical to the clustered events. In this area the seismic response seems to be primarily controlled by structures that could strongly react to blasts.

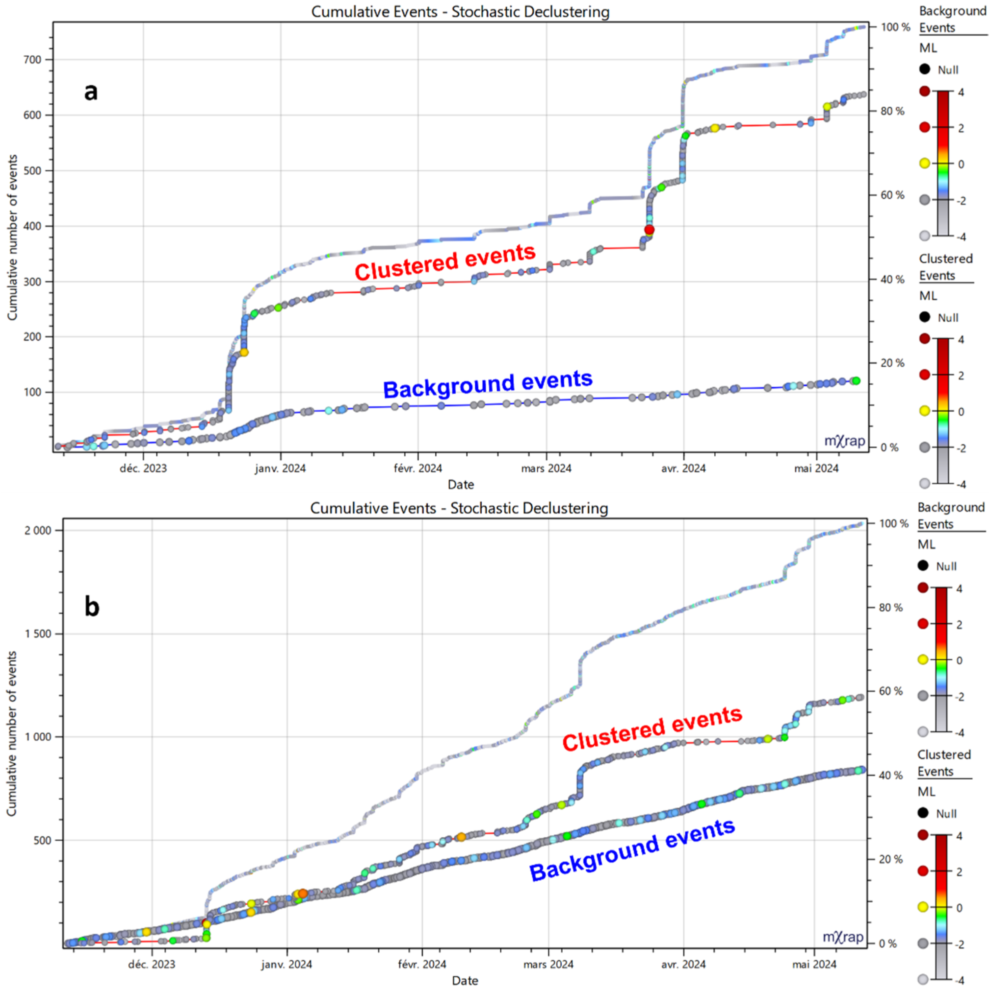

Figure 15 Cumulative events – stochastic declustering for different areas of the Westwood mine: (a) The southern part of the mine; (b) The central area of the mine

4.2.5 Others seismic analysis methods

Other aspects of seismicity are investigated in medium- and long-term seismic analyses, including seismicity of the structures, stope blasting assessment and seismic testing characterising stress migration.

4.2.5.1 Faults analysis

This consists of characterising the seismic behaviour of faults based on their likelihood of triggering a seismic event with a given ML. This is assessed using the maximum event triggered by the fault, its seismic activity rate and the variation of the b-value. The calculation method implemented in mXrap involves counting the number of seismic events within a 50 m radius of the fault. During this analysis, faults are evaluated over different periods including six months, 12 months and five years. This provides a good understanding of the evolution of the risk associated with the fault. For example, a decrease in the b-value indicates an increase in the risk level resulting in an increase in the maximum probable magnitude that could be triggered by the relevant structure. Following this evaluation the faults are classified into categories based on the maximum magnitude they could likely trigger.

4.2.5.2 *Stope blasting analysis*

The risk associated with extracting a stope can differ from the general risk of the area. These specifically focus on the seismic analysis of a stope. The objective is to identify the specific risks associated with blasting a stope and to formulate recommendations for reducing the associated risk. The elements evaluated in this seismic analysis include the sensitivity of the seismic system around the stope; the level of seismic risk around the stope; the probability of ML and its maximum likely to occur in the area, as well as its location relative to the stope to be extracted; the presence of particular structures or lithologies in the area that could react to the stope blasting; the expected seismic response and potential locations; whether exclusion measures are adequate for the anticipated risk, and the evaluation of seismic stresses that would make the extraction process complex and delicate.

4.2.5.3 *Stress migration analysis*

This method evaluates stress migration using the seismic response. Since seismic events are a response to stress change within the rock mass they are commonly used in numerical models as calibration elements. Consequently an interpretation technique of the seismic response has been developed at the Westwood mine to complement numerical models which characterise the short-term evolution of stress. In this analysis a cumulative distribution of the seismic response represented in 3D as isosurfaces is used (density 3D_mXrap). A comparative back-analysis of these isosurfaces with numerical modelling revealed that they could represent stress migration in seismic areas. Figure 16a shows the isosurfaces of a seismic response (post mining) while Figure 16b illustrates the results of numerical modelling with Phase 2 (pre-mining). The isosurfaces closely match with the stress concentration areas obtained from Phase 2. Therefore by following a blast, stress migration can be tracked using seismic response. The colours of the isosurfaces represent, from warmer to cooler, the 25th, 50th, 75th and 90th percentiles of the seismic response. The 50th percentile and below correspond to yielding zones while above the 50th percentile indicates areas of stress concentration. Additionally it can be observed that the highest apparent stress seismic events are located outside of the 50th percentile isosurface.

This analysis allows for the identification of stress migration following blasting in seismic areas. One of the practical uses of this analysis technique is the prediction of difficulties during longhole drilling. For example, the isosurfaces in Figure 17a show a concentration of stress in the middle part of the stope (red square, Figure 17a). The results from the Map3D model predicted a squeezing condition in the same location. A squeezing condition is obtained when the stress-to-strength ratio is between 0.3 and 0.7 (Hadjigeorgiou & Karampinos 2017). This prediction was confirmed during the drilling as the longholes in this stope experienced significant squeezing.

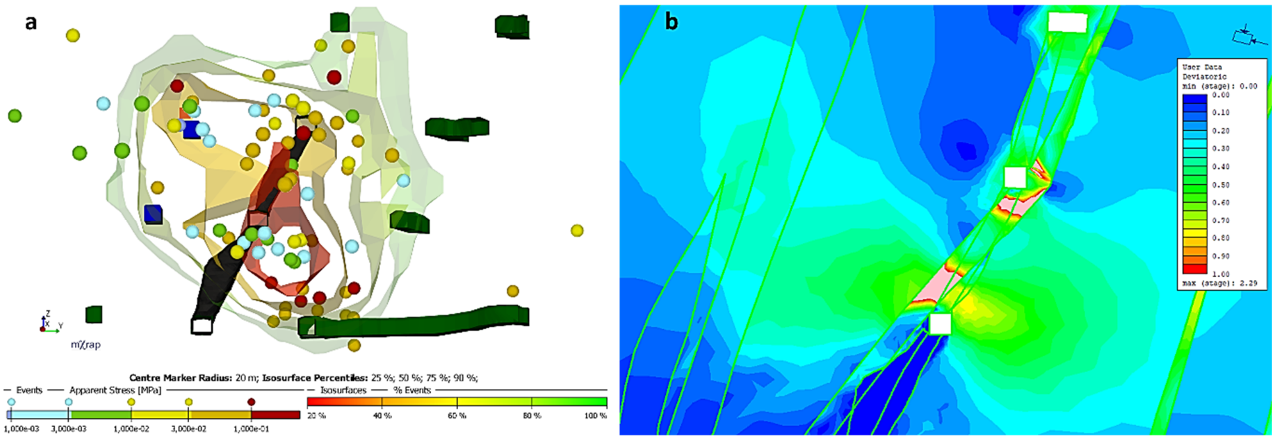

Figure 16 Stress migration analysis: (a) Isosurfaces of seismic response to blasting; (b) Phase 2 numerical modelling

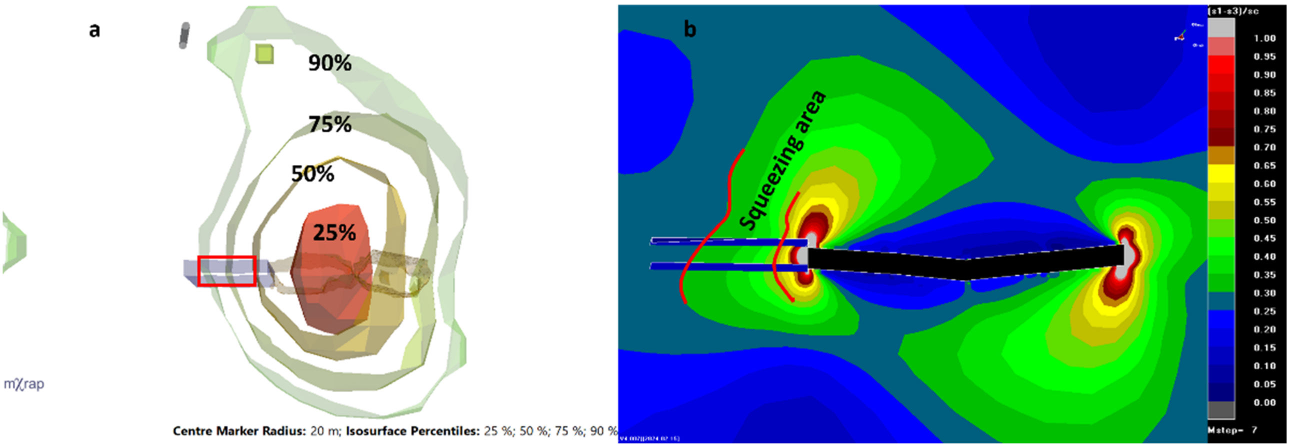

Figure 17 Stress migration analysis: (a) Isosurfaces of seismic response to blasting; (b) Map3D modelling

5 Conclusion

Managing seismic risk in mines operating under seismic conditions is crucial. Every mine operating in seismic conditions should have a risk management plan. This paper summarises the geoseismic strategy at Westwood mine in which various aspects of seismicity are employed to monitor seismic hazard with the goal of mitigating risk to an acceptable level. The techniques developed and the analysis methods used allow for a thorough characterisation of the rock mass based on its seismic potential, assessment of seismic risk by calculating the maximum possible magnitude in giving areas, and implementation of mitigation measures for anticipated risks such as changing the mining infrastructure placement/geometry and mining sequence, improving ground support, using a re-entry protocol measure and using a remote equipment. This strategy is an indispensable tool in the daily management of seismic risk at the Westwood mine, and we are confident that it could serve as a guide for other mines operating under similar seismic conditions. Through this strategy the seismic hazard appears to be effectively anticipated at the Westwood mine since operations were resumed in 2021.

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