## Seismic Wave Velocity Variations in Deep Hard Rock Underground Mines by Passive Seismic Tomography

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#### ABSTRACT

Mining engineers are tasked with ensuring that underground mining operations be both safe and efficiently productive. Induced stress in deep mines has a significant role in the stability of the underground mines and hence the safety of the mining workplace because the behavior of the rock mass associated with mining-induced seismicity is poorly-understood. Passive seismic tomography is a tool with which the performance of a rock mass can be monitored in a timely manner. Using the tool of passive seismic tomography, the advance rate of operation and mining designs can be updated considering the induced stress level in the abutting rock. Most of our current understanding of rock mass behavior associated with mining-induced seismicity comes from numerical modeling and a limited set of case studies. Therefore, it is critical to continuously monitor the rock mass performance under induced stress. Underground stress changes directly influence the seismic wave velocity of the rock mass, which can be measured by passive seismic tomography. The precise rock mass seismicity can be modeled based on the data recorded by seismic sensors such as geophones of an in-mine microseismic system. The seismic velocity of rock mass, which refers to the propagated P-wave velocity, varies associated with the occurrence of major seismic events (defined as having a local moment magnitude between 2 to 4). Seismic velocity changes in affected areas can be measured before and after a major seismic event in order to determine the highly stressed zones. This study evaluates the seismic velocity trends associated with five major seismic events with moment magnitude of 1.4 at a deep narrow-vein mine in order to recognize reasonable patterns correlated to induced stress redistribution. This pattern may allow recognizing areas and times which are prone to occurrence of a major

seismic event and helpful in taking appropriate actions in order to mitigate the risk such as evacuation of the area in abrupt cases and changing the aggressive mine plans in gradual cases. In other words, the high stress zones can be distinguished at their early stage and correspondingly optimizing the mining practices to prevent progression of high stress zones which can be ended to a rock failure. For this purpose, a block cave mine was synthetically modeled and numerically analyzed in order to evaluate the capability of the passive seismic tomography in determining the induced stress changes through seismic velocity measurement in block cave mines. Next the same method is used for a narrow vein mine as a case study to determine the velocity patterns corresponding to each major seismic event.

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#### GENERAL AUDIENCE ABSTRACT

Mining activities unbalance the stress distribution underground, which is called mining induced stress. The stability of the underground mines is jeopardized due to accumulation of induced stress thus it is critical for the safety of the miners to prevent excessive induced stress accumulation. Hence it is important to continuously monitor the rock mass performance under the induced stress which can form cracks or slide along the existing discontinuities in rock mass. Cracking or sliding releases energy as the source of the seismic wave propagation in underground rocks, known as a seismic event. The velocity of seismic wave propagation can be recorded and monitored by installing seismic sensors such as geophones underground. The seismic events are similar to earthquakes but on a much smaller scale. The strength of seismic events is measured on a scale of moment magnitude. The strongest earthquakes in the world are around magnitude 9, most destructive earthquakes are magnitude 7 or higher, and earthquakes below magnitude 5 generally do not cause significant damage. The moment magnitude of mining induced seismic events is typically less than 3.

In order to monitor mining induced stress variations, the propagated seismic wave velocity in rock mass is measured by a series of mathematical computations on recorded seismic waves called passive seismic tomography, which is similar to the medical CT-scan machine. Seismic wave velocity is like the velocity of the vibrating particles of rock due to the released energy from a seismic event. This study proposes to investigate trends of seismic velocity variations before and after each seismic event. The areas which are highly stressed have higher seismic velocities compared to the average seismic velocity of the entire area. Therefore, early recognition of highly stressed zones, based on the seismic velocity amount prior the occurrence of major seismic events, will be helpful to apply optimization of mining practices to prevent progression of high stress zones which can be ended to rock failures. For this purpose, time dependent seismic velocity of a synthetic mine was compared to its stress numerically. Then, the seismic data of a narrow vein mine is evaluated to determine the seismic velocity trends prior to the occurrence of at least five major seismic events as the case study.

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# Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

To my family

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# **Chapter 1 - Introduction**

Mining activities disturb the stress distribution in underground rock mass and might potentially cause hazardous rock failures, which damage mine tunnels and equipment and be fatal for miners in which case are called rockbursts. Seismic event is the general term for all kinds of failures in the rock mass that release massive energy. The safety of the underground mines can be improved dramatically by preparing for these events beforehand in order to mitigate their damage. However, the unknown nature of the underground rock mass is the major obstacle in this way. In order to foresee the potential damage as the result of inevitable seismic events, the seismicity of the rock mass subjected to induced stress can be monitored by using sensors and analytical methods called microseismic systems.

The seismic events release energy and can be detected based on the arrival time of the induced seismic waves to the sensors. Microseismic monitoring system is a tool to record the seismic wave propagation in the rock mass continually. Mathematical calculation of the recorded seismic waves, called seismic tomography, makes it possible to evaluate the velocity changes before and after each event. During a brittle failure the seismic velocity of wave in the rock mass increases until the initiation of the dilation, after dilation as the increasing distance between particles of the rock mass would be an obstacle in wave propagation thus the velocity variations can reflect induced stress until the extension of cracks at the onset of dilation in underground rock mass (Hea, et al. 2018). Therefore, the seismic wave velocity and seismicity can be potentially a precursor for stress accumulation. Moreover, studies show a change in seismic velocity of the rock mass when major seismic events occur and also the seismic velocity is highly elevated in highly-stressed areas in vicinity of mining (X. Ma, Passive Seismic Tomography and Seismicity Hazard Analysis in Deep Underground Mines 2014) (Molka, Tomographic Imaging Associated with a Mw 2.6 Fault-Slip Event in a Deep Nickel Mine 2017).

In this research, the trend of the velocity variations is evaluated to investigate the predictability of the occurrence of the seismic events. For this purpose, a better understanding of the underground induced velocity correlated to induced stress is required. This research is comprised of five articles. In the published first article, the potential of passive seismic tomography in investigation of the highly stressed zones is evaluated. In the second article, major changes in seismic velocity prior to each event are investigated. Next the daily difference in seismic velocity is evaluated to assess significant trends prior to the occurrence of events. The fourth investigates the subtle changes in seismic velocity in short time spans before and after each event considering the certainty of the calculation in order to find a precursory condition for event occurrence. The fifth article correlates seismic velocity with other seismic parameters such as b-value and Energy index in order to delineate a guideline for operation to proactively respond to seismic events in highly-stressed zones.

# **Chapter 2 - Literature review**

## 2.1 Introduction

The theory of rock mass failure in the lab-scale and field-scale is reviewed in this chapter. The influence of variations in mining-induced stress on seismic wave velocity propagation is investigated. Several studies show a correlation between applied stress and body wave velocity in the rock mass. This correlation is assessed in this chapter considering previous studies. Moreover, the application of passive seismic tomography in measuring induced seismicity and seismic wave velocity is reviewed and the common seismic tomography techniques are explained.

#### 2.2 Stress

Stress ( $\sigma$ ) is a tensor quantity defined as force (F) per unit area (A) as shown in Equation 2-1. General stress can be decomposed into the normal component or normal stress and tangential components or shear stress (Brady and Brown 1993).

$$\sigma = \frac{F}{A} \tag{2-1}$$

#### 2.2.1 Two Dimensional stress state

At a single point in two dimensions, stress is force per unit length and has two components in a single x-y plane. The component parallel to horizontal axis (x-axis) is normal stress ( $\sigma_x$ ) and the component perpendicular to the x-axis is ( $\tau_{xy}$ ) in the same order for y-axis  $\sigma_y$  and  $\tau_{yx}$  are defined. In rotational equilibrium, shown in Figure 1-2 by Goodman, shear stress will be equal; therefore, the stress at a single two dimensional elements is defined as Equation 2-1 (Goodman 1989).

$$\sigma_{xy} = \left\{ \sigma_x \, \sigma_y \, \tau_{xy} \right\} \tag{2-2}$$



Figure 2-1Stresses of a single element in two dimensions .

The normal and shear stresses are different on various planes. There is a direction with the angle of  $\alpha$  where shear stress is zero and normal stresses are minimum and maximum. These normal stresses are called major principal stress ( $\sigma_1$ ) and minor principal stress ( $\sigma_3$ ) (Hudson, Cornet and Christiansson 2003). Figure 2-2 illustrates the principal stresses with angle of  $\alpha$  and their values can be calculated by equations 2-3 and 2-4.



Figure 2-2. Principal stresses [from (Hudson, Cornet and Christiansson 2003)]

$$\sigma_1 = \frac{1}{2}(\sigma_x + \sigma_y) + [\tau_{xy}^2 + \frac{1}{4}(\sigma_x - \sigma_y)^2]^{\frac{1}{2}}$$
(2-3)

$$\sigma_2 = \frac{1}{2} (\sigma_x + \sigma_y) - [\tau_{xy}^2 + \frac{1}{4} (\sigma_x - \sigma_y)^2]^{\frac{1}{2}}$$
(2-4)

#### 2.2.2 Three Dimensional Stress State

In three dimensions, stress of an element is defined by normal and shear stresses on three planes of xyz coordinates. Hence a single element has three normal stresses and six shear stresses. These stresses will be addressed based on the plane they are acting on. Figure 2-3 demonstrates the stress state in three dimensions. The shear stresses acting on the same plane are equal based on the rotational equilibrium. Therefore, the symmetric matrix below defines the stress state in three dimensions (equation 2-5).

$$\sigma_{xyz} = \begin{pmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{xy} & \sigma_y & \tau_{yz} \\ \tau_{xz} & \tau_{yz} & \sigma_z \end{pmatrix}$$
(2-5)



Figure 2-3. The stress state in three dimensions [from (Goodman 1989)]

#### 2.2.3 Rock Mass Stresses

In rock mass the three normal stresses are sorted in two categories of vertical and horizontal stresses. Vertical stress ( $\sigma_v$ ) is equal to the weight of the overburden rock mass as shown in equation 2-6.

$$\sigma_v = \gamma z \tag{2-6}$$

where  $\gamma$  is the unit weight of the overburden rock mass and z is the depth (E. Hoek 2007) and (Goodman 1989).

The two other normal stresses are horizontal stress ( $\sigma_h$ ), which is usually equal to two initial tectonic stresses in depth. The average horizontal stress acting on a rock element in a certain depth (z) is relative to the vertical start at the depth by ratio of k. Equation 2-7 shows this relation (Terzaghi and Richard 1952).

$$\sigma_h = k\sigma_v \tag{2-7}$$

The sources of stress in the rock mass consist of four parts, the weight of the overburden rock mass ( $\sigma_v$ ), the pressure of surrounding rocks, external stresses such as earthquakes or excavation disturbance and the pore water pressure, which is the pressure of the water captured in the voids and fractures of the rock mass. Gravitational stress and the natural pressure of the initial tectonic stresses are called the in-situ stress applied to a single element of rock mass. The stress applied by construction or excavation activities to the rock mass is called the induced stress (Amadei, B and Stephansson 1997).

## 2.3 Rock Failure

Rock failure refers to the loss of integrity or cohesion of elements. It is dependent on the loading system of the rock mass. To define the strength of the rock as the maximum level of stress that rock mass can bear before it fails, laboratory tests on the rock sample are used. The most common tests to characterize the strength of the rock specimen are unconfined and confined compression tests, shear tests, tension tests (Goodman 1989).

In failure analysis of rock mass, the measured strength of the rock specimen in the laboratory represents the intact rock mass strength. In failure of a simple element of the rock mass,  $\sigma_1$  is the peak stress and  $\sigma_3$  is the confining stress. Failure Criterion refers to the relationship between the state of stress and the strength parameters of rock when the

rock is failing. Generally, it can be expressed as the equation between the principle stresses under the ultimate stress state:  $\sigma_1 = f(\sigma_2, \sigma_3)$  or  $\tau = f(\sigma)$ .

#### 2.3.1 Mohr-Coulomb Criterion

Mohr-Coulomb criterion is one the most common failure formulation for isotropic materials. It uses Mohr's circle which is drawn by normal and shear stresses and determines cohesion of the rock remains constant while friction differs by normal stress (Hoek and Brown, Underground Excavations in Rock, 1980). Equation 2-8 shows this relation and Figure 2-3 illustrates this criterion in graphics.

$$\tau = c + \sigma_n \tan \tan \varphi \tag{2-8}$$

where  $\tau$  is the peak shear strength, c is the cohesion,  $\sigma_n$  is normal stress and  $\varphi$  is the angle of internal friction. The internal friction angle is similar to the friction angle between two surfaces of a slide. In the graphical of the failure criterion,  $\beta$  stands for the angle between failure plane and the minimum principal stress  $\sigma_3$ . Several studies evaluated this criterion in rock mechanics modeling and experiments (Labuz and Zang 2012; Zhao 2000).



Figure 2-4. Shear and normal stress in the Mohr-Coulomb criterion (a) for a shear failure plane A-B (b) [after (Zhao 2000)]

Other than Mohr-Coulomb criterion, Hoek-brown failure criterion introduced an empirical formula as shown in Equation 2-9, in which m<sub>i</sub> and s are material constants for a specific

rock and  $\sigma_c$  is uniaxial compressive strength (Hoek and Brown, Underground Excavations in Rock, 1980).

$$\sigma_1 = \sigma_3 + \sigma_c \sqrt{m_i \frac{\sigma_3}{\sigma_c} + s} \tag{2-9}$$

#### 2.3.2 Brittle Rock Compressive Failure

The deformation of rocks under unconfined stress is abruptly destructive at the maximum strength as the result of the sudden release of the strain energy (Rummel 1972). The brittle failure of an intact rock under uniaxial stress reveals different stages in the stress to strain curve that several studies examined and graphed for different types of rock specimens (Goodman 1989; Martin and Chandler 1994; Harrison and Hudson FREng 2000; Bogusz and Bukowska 2015; Zhou, Xia and Zhou 2017). The most complete depiction was done by Hoek and Martin (2014) based on several experiments of various intact rock specimens (Figure 2-5); and four stages of failure were determined by measuring both strain and acoustic emission (Hoek and Martin, Fracture initiation and propagation in intact rock – A review 2014).

During the rock mass failure, the rock specimen subjected to deviatoric stress, comprising unequal principal stresses, first demonstrates an inelastic increase in its normal strain as the result of the closing fissures and pores (yellow point in the figure marked as crack closure stage). A linear elastic trend follows this stage until all fissures and pores are closed and new cracks appear and extend to their maximum length (crack initiation stage shown with a red dot). The axial stress-strain curve reaches its yield point after the extension of cracks reaches to the edge of the specimen (defined as the onset of strain localization with a blue dot). Then the microcracks density increases until the stress gets to its peak where the stress-strain curve reaches maximum axial stress (reaching to the peak shown with a yellow dot). The rock, however, may not collapse at this point as microcracks are merging continually until generating macrocrack, the fractured rock slides on the macrocrack surface (Goodman 1989; Hoek and Martin, Fracture initiation and propagation in intact rock – A review 2014).

Although the volume of the rock specimen shrinks at the beginning of the compression by closing the fissures and pores, it starts to expand after the initiation of the cracks and their growth. This increase in volume might enhance the bulk volume of the rock to larger than its initial value. The volume expansion as the result of the cracking in the rock under the compressive stress is called dilatancy or dilation.



Figure 2-5. Four different stages in intact rock failure under compressive stress based on stress-strain curve [from (Hoek and Martin, Fracture initiation and propagation in intact rock – A review 2014)]

#### 2.3.3 Underground Rock Mass Failure

Existing intermittent discontinuities in the rock mass create the rock bridge failure condition. Rock mass includes fractures in different extends and the majority of rock mass failures involve the extension of preexisting fractures. The mechanism of the rock bridges is complex and ambiguous in underground failures. Wong and Chau (1998) measured and model a similar stress-strain curve for Sandston including intermittent fractures (Wong and Chau 1998).

In the field scale, when the applied compressive stress due to the weight of the overburden is high, the tensile fractures are extending with a low constant rate; therefore, the rock mass failure is gradual. Shear fracturing, however, may cause a destructive failure when compressive stress is high. Moreover, around the underground openings, the spalling mechanism is observed due to the increase in tangential stress and partially eliminates the confining stress (Shen and Barton 2018).

### 2.4 Induced Stress

Any change in the rock such as excavation of a tunnel disturbs the balance of the in situ stresses and causes new stress set in the rock around the excavation. The new set of stresses in the surrounding rock is known as induced stress and its measurement is necessary for engineering designs for construction and maintenance of any excavation (E. Hoek 2007). Spalling is the main failure mechanism around the mine openings in the hard rock underground mine (Hidalgo 2013).

The rock mass stresses are categorized into two states of before disturbance to in-situ stress and after application of induced stress respectively (Amadei, B and Stephansson 1997). Before the disturbance, horizontal stresses ( $\sigma_{h1}$  and  $\sigma_{h2}$ ) acting on an element of rock are similar. After the disturbance, the stresses in the influenced area are changed and new principal stresses acting on the rock elements are induced (E. Hoek 2007).

## 2.5 Induced Seismicity

The term seismicity is used for earthquakes distribution on the earth which has a natural source (USGS, Earthquake Glossary 2016). Human disturbance, which affects stress distribution on Earth, will cause minor shakes in the surrounding rock. These small scale tremors are known as induced seismicity. Induced seismicity is caused by activities that unbalance the stress equilibrium in rock mass such as mining, fluid injection, underground constructions, and groundwater extraction. In addition to the induced stress, tectonic stress might be released by induced tremors (Foulger, et al. 2018).

#### 2.5.1 Seismic Velocity

Any natural or artificial disturbance in the earth that causes displacement initiates a seismic wave propagated in the rock mass. The initial source of the seismic wave is described as a seismic event. The travel rate of the seismic wave through the earth is seismic velocity. Seismic waves propagate in two main forms of body waves and surface waves through an elastic body (Wu and Wu 2008). The velocity of wave propagation is based on the rock mass properties such as density, porosity, lithification, pressure, and saturation (Keary and Brooks 1991).

Body waves arrive first and are in two kinds of primary (p-wave) and secondary (s-wave). P-waves are the fastest waves and arrive first. They are compressional along longitude. Swaves arrive second and are shear waves that shake the ground perpendicular to the direction of propagation (Shedlock and Pakiser 1995).

Surface waves arrive later along the earth's surface and cause stronger vibration on the surface. There are two kinds of surface waves: Love and Rayleigh. Love waves propagate through layered material. They cause side-to-side horizontal displacement. Rayleigh waves are the slowest waves, which arrives last. They cause horizontal displacement in the direction of propagation and vertical displacement perpendicular to that (Shedlock and Pakiser 1995).

Stress distribution and seismic velocity are related. Areas with higher velocity correspond to higher stress concentrations by consideration of void ratio and compaction (Kerr 2011). Additionally, high seismic velocity can reflect the high stiffness of the rock properties. (Blum 1997). Velocity directly rises with depth, as confining pressure and weight of overburden rock mass increases with depth.

#### 2.5.1.1 Seismic Velocity Determination

The seismic velocity of P-wave and S-wave can be determined by the known density and elastic moduli of P-wave as shown in Equation (Kearey, Brooks and Hill 1991). As the determination of these values for rock mass is not accurate, the velocity lab test can determine the seismic velocity of a rock specimen (Kerr 2011). However, a rock sample may not be a good representative of the rock mass in terms of the velocity, because of variations of the structures and fractures in the rock mass (Moos and Zoback 1983). In situ testing provides the most accurate seismic velocity values by the use of a seismic survey.

#### 2.5.2 Mining Induced Seismicity

Failure may occur in rock mass as the result of the induced stress in the vicinity of the mining excavation. The rock failure is the source of seismic wave propagation in this environment which is a low magnitude seismic event. Rockburst is known as the destructive seismic events which may cause fatalities and damage (Gibowicz 1995). Rockbursts' magnitudes rarely exceed more than 5, which can be felt (Blake and Hedley, Rockbursts: Case Studies from North American Hard-Rock mines 2003).

Mining induced seismic events can be direct as the result of the mining operations or can be caused by geological discontinuities. Rock failure occurs at or adjacent to the active mining face and is initiated by mining operations thus the seismic events induced by them have lower magnitude compared to the average magnitude of the events in the area and occur in weak zones of the rock within 100 m from the mining face. The number and time of these events are correlated with mining activities. The seismic events associated with geology have a larger magnitude at further distances from the mining face. They seem to be affected by the entire mine seismicity than a specific mining area therefore their occurrence time is more random (Gibowicz 1995).

### 2.6 Seismic Monitoring

The release of elastic energy as the result of ground movements generates seismic waves (L. W. Braile 2009). The seismicity of earthquakes is recorded by seismograms installed around the world. Global Seismograph Network (GSN) and Federation of Digital Broadband Seismic Networks (FDSN) monitor seismograph stations around the world. Incorporated Research Institutions for Seismology (IRIS) and U.S. Geological Survey (USGS) display the updated earthquake records online (IRIS 2016) and (USGS 2016). Regional networks are also added to this network supported by university groups (Swanson, Boltz, and Chambers 2016).

Frequency range coverage of the global, regional and Broadband seismic networks are lower than a system of seismic or acoustic sensors installed in a mine. Hence, lower magnitude seismicity with higher frequency can be monitored better by in-mine seismic networks (Swanson, Boltz, and Chambers 2016).

Seismic monitoring requires instrumentation and precise analysis of data. Geology structures under high stress generate micro fractures which induce seismic waves in the rock mass. At a specific point, a suitable installed sensor can detect the velocity or acceleration of these waves. In relatively high-frequency waves (more than 2000 Hz) accelerometers have the best application. In contrast, low-frequency signals (less than 1 Hz) are detected with displacement gauges. Signals in between these extremes can be covered by geophones (velocity gauges). The sensitivity of acceleration transducers is independent of the mounting angle in contrast with velocity and displacement gauges (Drnevich and Gray 1981).

In mining, seismic monitoring started by acoustic emission monitoring techniques by installing transducers and receivers. The first application of acoustic monitoring was for coal underground mines in the 1960's and since then several researchers developed the application of the technique to hard rock underground and surface mining (Drnevich and Gray 1981). By time different sensors replaced acoustic transducers such as geophones, hydrophones, and accelerometers to monitor seismic velocity.

### 2.7 Seismic Tomography

Tomography is a general term for the technique of picturing the internal and invisible structures of the solid body using interpretations on the wave or energy passed through the body, the final picture can be a three-dimensional model or two-dimensional cross-sections. The best example is the CT scan, which is a tomography device using an X-ray wave. Seismic tomography is using seismic waves either induced or natural to image the interior earth (Iyer 1989). Seismic tomography can be used to identify the physical properties of the interior of the earth remotely and illustrate the earth's interior structures and stress distribution by analyzing seismic wave velocities. Seismic tomography was introduced to image the seismic zone based on the P-wave and S-wave travel times (Aki and Lee 1976) (Nolet 1978).

Seismic tomography can be active by using artificial and known emission sources for seismic wave propagation or passive by considering natural seismic events as the seismic wave propagation source. The locations of the sources of energy are random in the passive method (Thurber and Ritsema, Theory and Observations – Seismic Tomography and Inverse Methods 2007).

#### 2.7.1 Velocity Models

Seismic tomography is based on the travel time of seismic waves which refers to the velocity of the wave propagation and determination of its source location. The location of the seismic source will be defined as the result of the model. The velocity model is a method to calculate the velocity of the waves through the ground to image the seismic tomography. Geiger's method was the first introduced technique for locating earthquakes based on the

least square regression of the observed first P-wave arrival times (Geiger 1912). Extending Geiger's method, Aki and Lee (1976) introduced the simplest velocity model to image a homogeneous case with constant P-wave velocity. They defined a mesh network in a rectangular area and formulated an initial model with a matrix of linearized equations for the first P-wave arrival time (Aki and Lee 1976). According to their study, the quality of the tomographic image is based on the number of seismic events and the number of receivers. The amount of source events is fixed while the number of receivers can be increased to get a better image (Aki and Lee 1976).

The S-wave travel time in low-velocity zones was calculated by Nolet in 1978. This resolution uses linearization to calculate the shear velocity of body waves (Nolet 1978). Aki et al. and Nolet studies focused on local-scale body and surface waves respectively (Thurber and Ritsema, Theory and Observations – Seismic Tomography and Inverse Methods 2007). However; Dziewonski and his coworkers developed global-scale tomography for the body- waves (A. M. Dziewonski 1977; Dziewonski and Woodhouse 1987).

An initial velocity model is first derived from a weighted average of data. Velocity model development is through an inversion process which means it starts with the result data and will calculate the cause. Propagated velocity through the earth's interior is defined by the initial velocity model and its predictions will be compared with actual observation. Modifications are applied to the initial model and this procedure continues to obtain an acceptable degree of similarity. The developed model is a one-dimensional (1-D) velocity model which is the reference model for a three-dimensional (3-D) model (Kissli, et al. 1994). Seismic tomography methods are based on 3-D velocity models.

# 2.8 Background Applications

Early studies of tomography in the geotechnical field goes back to 1939 for hard rock mines. It slightly found its way into coal and salt mining since the 1950's (H. Reginald Hardy 2003). The detailed list of studies from 1939 to 1995 is listed by Hardly Jr. with

emphasis on geotechnical and mining applications. Since 1993 transducers were mounted in underground and then surface mining to determine the failure and rockburst hazards (Drnevich and Gray 1981). Seismic monitoring also has been used for environmental assessments, ore deposits, locating fractures in rock formation and determining velocities and stress of rock formations (Xu, et al. 2000). Seismic monitoring has been used to distinguish rock failure mechanisms at mines whether they are progressive, continuous, or episodic (Kerr 2011).

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# Chapter 3 - Review and Simulation of Passive Seismic Tomography in Block Cave Mining

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## 3.1 Abstract

Seismic tomography methods are progressing in crustal seismology and, at the smaller, mining scale to recognize highly-stressed or fracture-prone areas. Velocity variations measured by seismic tomography represent stress concentrations in the rock mass. Changes in these stress conditions are of interest in mining as they are linked to the instability of the underground openings. Rock fracturing generates seismic waves, which propagate with different velocities through portions of the rock mass that have different moduli.

Both known and unknown seismic sources in mining environments generate active and passive tomography data, respectively. Active tomography utilizes a known source time and location while passive seismic tomography uses the mining-induced seismic events, for which the source time and location can only be estimated. Mining-induced seismic events generally have relatively low magnitudes, typically lower than ML=3.

The pattern of stress redistribution varies based on different mining methods at different depths. In this study, development of seismic tomography in the mining industry is traced through a review of background theory and recent applications. Additionally, a block caving simulation is presented, including the imaging of cave development, load distribution, and abutment zones. A simple elastic numerical model is used to model stress distribution surrounding a hypothetical block cave. Velocities are assigned to portions of the model corresponding to the stress level. With this velocity model, synthetic travel times

are modelled. The synthetic travel times are then used as input to the tomography code. The velocity distribution which is then generated through the tomography calculations is compared to the initial, modeled velocity distribution providing a means for validating the quality of the results of the tomography approach for this application.

### **3.2** Introduction

One of the most significant challenges of block cave mining is the unknown condition of abutment loading in the rock mass. This has a material impact upon safety and production. Movement along with structures and rock deformations affect abutment stress distribution conditions (Han et al. 2014). Therefore, it is relevant to track rock mass deformation in the early stages of potential failures in order to mitigate ground movement hazards, which benefits both safety and production. For this purpose, the high-stress areas have to be identified and destressed. Direct measurement of underground stress in abutment rock is not easily achieved, particularly at full scale, in mining (Hoek et al. 2000). Petr et al. (2016) applied strain gauge probes as a reliable tool to measure in situ stress of rock mass. The applicability of such methods for the discrete measurement of stress changes in the rock mass has limitations with respect to the ability to process the information in real-time, as well as the number of instruments that can practically be installed in a given region. External factors such as regular drilling and blasting might apply excessive energy to unknown underground discontinuities, which may not have been interpreted and mapped as a result of exploration or pilot drilling.

Passive seismic tomography allows for the indirect measurement of underground stress in abutments. This proactive approach to ground control hinges upon indirectly determining the seismic velocity changes in the rock mass, which is directly correlated to the stress. Stress redistribution can be visualized by applying seismic velocity tomography on a temporal scale.

This study proposes that the zones identified with high velocity in the abutment in situ rock mass and the fractured rock above the caved area in a block cave mine represent the areas

with the most concentration of the induced stress. For this purpose, the seismic velocity tomograms are compared with the numerical analysis of stress.

### **3.2.1** Computed Tomography

Computed or computerized tomography (CT) uses computer-processed calculations to model an object via cross-sectional images from different angles which are generated by any wave which can penetrate the object and be measured (Herman 2009). The penetrating wave can be an X-ray, an electrical wave, an acoustic wave or even a seismic wave. For example, CT scan machines used in medical imaging use X-rays to penetrate the human body. The inside of the solid body, which the wave passed through, can be modelled using tomography. In this method, the wave velocity through a homogeneous material is considered constant. Knowing the travel time of the wave can allow us to determine the origin of the wave. Wave attenuation for specific materials can also be characterized; therefore, any changes in the wave travel time are due to changes in structures or material inside the body. However, the solution is not unique spatially due to a limited number of received waves used in the chosen tomography method. Any known source and velocity of the wave through the body are essentially valid for calculations.

Seismic velocity refers to the velocity of the body waves in the rock mass. Body waves include P-wave and S-wave, which propagate inside the solid rock in compression and shear respectively. The P-waves travel faster and are received first after the occurrence of a seismic event. Seismic tomography is based on the travel time of these waves inside the rock mass. The travel time of a seismic wave through the rock mass gives an average of the wave speed (also known as the apparent velocity) along the wave's ray path, which is the path that seismic wave travels from the source to the receiver.

In this method, a homogeneous initial model of constant P-wave velocity is considered to determine the dominant velocity of the rock mass as the medium (Westman 2004). The source of P-wave propagation, which is termed the seismic event, can be a micro-scale crack in the rock mass with the local magnitude of less than 3. The origin location and

time of the seismic events are considered as the source parameters. Therefore, the source and medium parameters will be determined based on the best fitted P-wave arrival time in the least squares solution.

#### 3.2.2 Seismic Tomography

The common seismic tomography methods are transmission tomography, diffraction tomography, attenuation tomography, travel time tomography and double-difference tomography. These methods are according to whether time travel data or waveform data are utilized (Kerr 2011).

Transmission tomography is based on the inversion of travel times of P-waves. Diffraction tomography is the inversion of the reflected wave, which is scattered by the targeted object, in order to remodel the cause of scattering. Diffraction tomography can have the same resolution as transmission tomography with less coverage of sources and receivers (Peterson et al. 1989).

Attenuation tomography is based on the seismic amplitude and was developed for X-ray application in the medical field. It requires the waveform data in addition to the simple arrival time (Bauer et al. 2005). In seismic tomography, this method is less practical as it is highly affected by numerous unmeasurable properties of rock, such as the viscosity of interior layers (Watanabe & Sassa 1996).

Time travel tomography has the most application in seismic velocity modeling (Farzampour & Kamali-Asl 2015; Fehler & Rutledge 1995). In this method, the area of interest is divided into blocks. The best prediction of the velocity of each block is calculated based on ray path shortest travel time and damped least squares solutions. The residual of the predicted and observed travel times should be smaller than a defined error to stop the iteration of the process (Schuster 1998; Watanabe & Sassa 1996). This method can be applied in both passive and active tomography. Different inversions of this method might apply hyperbolic or parabolic regressions based on its specific application (Fehler & Rutledge 1995).

To calculate the travel time of waves the quantitative concept of slowness is defined. Slowness is the inverse of the velocity of the wave and is the result of the different layers of the earth. As in Equation 1 the time travel is the integral of each block's slowness (1/velocity) along the ray path (Stein & Wysession 2009).

$$S(s,r) = \int_{s}^{r} \frac{1}{v(x)} dx$$
(3-1)

in which S is the slowness based on source (s) and receiver (r), v is the velocity of each block and x refers to the block number.

Double-Difference (DD) tomography is a relatively new variation of time travel tomography. This mathematical method was first introduced by Zhang and Thurber (2003) for near-source seismicity and was developed to be applied in hard rock underground mining by several studies, such as (Kerr 2011; Ma 2014).

### 3.2.3 Passive Seismic Tomography Algorithm

In passive seismic tomography, based on the travel time, the inversion of the velocities of received waves is applied to estimate the velocity of different nodes in the rock mass. Several iterations are required to determine the most accurate estimation of the travel times. The rock mass volume is divided into smaller volumes named voxels (Brzostowski & McMechan 1991). Each received seismic wave passing through different voxels is known as a ray (Molka 2017).

The tomography algorithm is based on the linear equation of Ax=b in which b is the travel time residual and x is its received image or slowness perturbation in travel time tomography. A is the forward projection matrix including the distance traveled by each ray (Rawlinson et al. 2014). The travel time residual b is the time difference between observation and measurement.

There are several methods to solve this equation for the velocity of each voxel such as Gauss-Newton, Algebraic Reconstruction Technique (ART), Partially Discrete Iterative

Reconstruction Technique (PDART), and Simultaneous Iterative Reconstruction Technique (SIRT) (Molka 2017).

The SIRT algorithm suggests the tomography solution with the inverse of the summation of rows and columns of the matrix A, which represents the projection source characteristics.  $A^{T}$  is the transposed matrix which back projects the image and defines which voxels are exposed to a single ray as shown below (Roelandts 2014):

$$x(t+1) = x(t) + CA^{T}R (b - Ax(t))$$
 (3-2)

where C and R are diagonal matrixes of inverse summations as  $c_{jj} = 1/\sum_i a_{ij}$  and  $r_{jj} = 1/\sum_j a_{ij}$  and t is the iteration number. The iterations start where  $x^{(0)}$  is equal to zero. The optimum number of iterations can be defined based on the elbow of the time residual and the number of iterations graph.

### 3.2.4 Passive Seismic Tomography Application in Mining

Early studies of microseismicity in the geotechnical field go back to 1939 for hard rock mines. It gradually found its way into coal and salt mining during the 1950s (Reginald Hardy 2003). Since 1993 transducers were mounted underground and then surface mining to determine the failure and rockburst hazards (Drnevich & Gray 1981). Since the 1980's, seismic monitoring systems have been used in underground mining with different mining methods such as cut and fill, block caving and sublevel caving to control rockburst (Trifu & Sourineni 2009). Seismic attenuation tomography was introduced as a tool for in situ rock mass characteristics in 1996 (Watanabe & Sassa 1996) and acoustic transmission tomography was used to map the underground rock walls in an underground power plant (Song et al. 1998). Seismic monitoring also has been used for environmental assessments, ore deposits, locating fractures in rock formations and determining body wave velocities and stress in the rock samples (Xu et al. 2000).

Several underground hard rock mines, such as block cave mines (Westman et al. 2012) and cut and fill (Ma 2014), have used the microseismic system to record the seismicity of the

mine and conduct passive seismic tomography examining stress redistribution associated with major seismic events. Rock performance analysis, however, is not very straightforward using the recorded seismicity as there are several considerations in the system installation. The area subjected to passive tomography should have a sufficient number of sensors so that there is thorough raypath coverage for each voxel (Westman 2004). The orientation of the rays is also important to reconstruct a high resolution velocity model. The smearing of the tomogram can also influence the accuracy of the velocity model when the majority of large events are close to each other and at some distance away from the sensors (Molka 2017).

Moreover, the background noise should be less than the incoming P-wave amplitude. Therefore, the sensors are recommended to be mounted not very close to the operation level. Additionally, sensor locations have to be stable and not damaged by blasting or other mining activities.

## **3.3** Methods and Procedure

In this study, a hypothetical block cave mine is considered in a homogeneous rock mass with no tensile strength and cohesion of 5 MPa. The horizontal stress of the model is considered zero. A section of the mine including 9 drawpoints is designed with an overburden depth of 730 m. Figure 3-1 shows the dimensions of this section. The caved zone above this section has a maximum height of 325 m.



Figure 3-1. Dimensions of the designed section with 9 drawpoints

This section is simulated by Linear Elastic Boundary Elements Method to model the induced stress. The induced stress at each node is considered as the cumulating of the three principal stresses. The average stress of the model is calculated and based its variations the velocity model is generated. The caved zone is considered as the void in this model. High-stress zones are the areas with stress greater than the average stress. A total of 430 seismic events were generated in these high-stress areas randomly. Moreover, 32 seismic receivers were designed in the rock mass around the caved zone. Figure 3-2 shows the location of these sensors around the mining section.



Figure 3-2. Sensors locations, A) side view, B) front view

In order to determine the effect that varying number of ray paths have on the calculated results, three different data sets are analyzed. The three datasets had 1000, 5,000 and 20,000 synthetic raypaths. The expectation is that better images would be calculated with more raypaths. Figure 3-3 illustrates the event associated with these different datasets. As it is shown 20,000 raypath results (shown in Figure 3-3-C) involve more events. The Fast Marching Method was used to simulate raypaths that refract toward high-velocity zones and around low-velocity zones. Based on the calculated travel times the seismic velocity of the rock mass is measured through the SIRT algorithm and high and low-velocity zones are generated.



Figure 3-3. Event locations, for A) 1,000 raypath results, B) 5,000 raypath results, and C) 20,000 raypath results

### **3.4 Results and Discussion**

The numerical model of the induced stress for our block cave section shows high-stress areas above the caved zone and in the abutment zones. As a result of this numerical analysis, the average stress of this section is 90 MPa with a standard deviation of 5.6 which is 6% of the average stress. High-stress zones are areas with isostress level of equal or more than 93 MPa as demonstrated in Figure 3-4. The average velocity is considered as 6000 m/s to form the velocity model with a standard deviation of 6% of the average velocity. Therefore, the first quartile of the velocity distribution is 5975 m/s.



Figure 3-4 A) Isometric view of modeled block cave, B) Isometric view of modeled stresses around block cave. Purple is 70 MPa isostress level, yellow is 93 MPa isostress level.

The stress distribution at a vertical cross-section passing through the midpoint of the block cave is numerically modeled and shown in Figure 3-5-A. The modeled stress distribution is compared with the simulated velocities at the same cross-section, shown in Figure 3-5-B. Total induced stress is shown in units of megapascals and velocities shown in units of meters per second.



Figure 3-5. A) Cross-sectional view of modeled stresses around block cave at the midpoint, B) Crosssectional view of simulated velocities around block cave, based on modeled stresses. The cross-section is taken at the midpoint of block cave

Results from the tomography calculations show a velocity distribution that is similar to the modeled stress. The low-velocity cave is seen in each of the three results. Figure 6 demonstrates the effect of the number of raypaths in calculated velocity. As expected, the results using the most raypaths (shown in Figure 3-6-C) most closely agree with the expected results. On the other hand, the results using the fewest raypaths (shown in Figure 3-6-A) are somewhat smeared due to the lack of raypaths. Additionally, with fewer raypaths, the low-velocity zone is not imaged as accurately as there are fewer raypaths associated with it.



Figure 3-6 Cross-sectional view of calculated velocities around block cave, for 1,000 raypath results, B) 5,000 raypath results, and C) 20,000 raypath results. The cross-section is taken at the midpoint of the block cave. Velocities are shown in units of meters per second.

## 3.5 Conclusion

Passive seismic tomography enables the indirect measurement of induced stresses in the rock mass. In the context of a block cave mine, this information may assist with operational controls to safely extract the ore. The technique can assist mine operators to identify zones with high seismic velocity in the cave abutment as well as the fractured rock above the caved area. The high seismic velocity zones in the mine represent the areas with the most concentration of induced stress. This study investigates seismic tomography as a remote tool to image the interior of a rock mass, which can measure seismic velocity changes in the rock mass as representative of the induced stress. As the result, high-stress zones in a numerical model of block cave mine are in agreement with the high-velocity zones measured through the synthetic ray paths. Based on the results of this study, the seismic tomography using SIRT algorithm has high potential to monitor induced stress distribution in block cave mines.

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# Chapter 4 - Time-dependent monitoring of seismic wave velocity variation associated with three major seismic events at a deep, narrow-vein mine

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### 4.1 Abstract

One of the most difficult challenges in underground mining is to forecast significant seismic events prior to their occurrence in order to support the safety of miners and to minimize damage to the underground operation. Passive seismic tomography is a tool to image the seismic velocity changes in a rock mass, which can potentially reveal the rock mass behavior before and after a significant seismic event. In this paper, the changes in the seismic velocity of the rock mass before and after three major seismic events are investigated to determine whether there are identifiable precursory velocity changes associated with the major seismic events. Conventional mechanics imply that the induced stress at the hypocenter would continue increasing until failure, in the form of an induced seismic event, occurs. With passive seismic tomography, we can image changes to the seismic wave velocity distribution within a rock mass and hence infer the changes to the induced stress near the hypocenter. This paper evaluates the hypothesis that induced stress at the hypocenter (as inferred by the P-wave velocity) increases until the seismic event occurs. In addition to analyzing P-wave velocity changes near the hypocenter, changes to the P-wave velocity at 'zone centers' were also analyzed. These 'zone centers' are regions within the rock mass that consistently have a P-wave velocity that is much higher than the average P-wave velocity for the rock mass. It is found that the P-wave velocity did not increase at any of the three hypocenters prior to the seismic event occurring; however, the P-wave velocity did increase in the closest 'zone center' for two of the three events.

## 4.2 Introduction

As an underground ore deposit is mined, the excavation process results in concentrations of increased induced stresses. Accumulation of this stress can cause instabilities that can be hazardous. The partial or general instability of the roof and ribs in underground mines is the main cause of ground falls, which have resulted in multiple injuries and fatalities (Biswas and Zipf 2003). Rockbursts are any volumetric displacement in underground rock that causes damage with any magnitude within the mine (Blake and Hedley 2003; Foulgar et al. 2018). Although the number of fatalities associated with rockbursts is significantly less than other types of underground hazards such as fires or inundation, they are considered one of the more significant potential hazards due to their perceived random nature and a high potential for injury or death. Fatalities associated with rockbursts have decreased over the last 50 years as a result of successful research efforts toward understanding how bursts are initiated, an increasing number of mines installing underground seismic arrays around mining volumes, and the development of mining methods to decrease their occurrence and mitigate associated damage. Nevertheless, rockbursts still occur and represent a significant hazard to underground miners. With modern mining progressing to increased depths, the potential for damaging rockbursts is still very real and the development of techniques to help forecast them is an active topic of research.

A safe mining environment is the ultimate goal of each mine. The inclusion of modern technology and instrumentation, such as real-time seismic monitoring, have aided in achieving this goal in many aspects including rockburst hazard mitigation. An advancement that would be beneficial is to develop tools for underground mines that are comparable to slope stability radar at a surface mine—i.e. a real-time three-dimensional method for monitoring changes within the rock mass. Seismic tomography has the ability to fulfill this need, and although tomographic techniques are not new, the computing power of modern desktop computers has made seismic tomography feasible for proactive ground control data processing and analysis. The tomography results can be used to monitor the

highly-stressed areas underground. The ultimate goal of microseismic tomography applied in underground mines is to have an alert system for a mining operation to reduce their mining advance or completely avoid the zones subjected to induced stresses when the stress concentration is critical.

This study presents the results of a velocity tomography back-analysis utilizing a yearlong seismic catalog from a selected seismogenic volume within a deep, narrow-vein, hard rock mine that contained three major seismic events. The seismic velocity changes within the volume are evaluated before and after the three major seismic events in order to examine whether there is an identifiable pattern of velocity changes associated with the events. The velocity tomograms were calculated on a weekly basis, and high- and low-velocity zones were determined around the mining location for each week of the recorded data. The objective of the study was to test the hypothesis that the P-wave velocity near the hypocenter increases prior to the occurrence of the major seismic event.

## 4.3 Background

"Seismicity" is the frequency of the occurrence of seismic events—e.g. earthquakes. "Induced seismicity" is the energy released by fault slips or rock failure due to human activities, such as mining activities or fluid injection. Mining activities disturb the static loads and the stress redistribution results in local areas of increased stress within the rock mass, typically resulting in induced seismicity when the stress level exceeds the strength of the rock mass at a location.

Any spontaneous source of initiation of the seismic wave transmission in the rock mass is called a "seismic event" (Kamie et al. 2015). The energy released by seismic events is measured in different scales. The Richter magnitude scale, known as the local magnitude  $(M_L)$ , is based on the logarithm of the measured ground horizontal displacement, which depends on the distance of the receiver from the source. This method was developed in the early 20<sup>th</sup> century and is commonly used for reporting earthquake magnitudes to the public due to its historical use. The moment magnitude scale  $(M_w)$  is based on the seismic

moment, which includes more elements such as the average amount of slip and the required stress for the rupture. This is a more common and comprehensive scale used by the seismological community and is especially useful for large earthquakes recorded at a distance (Baruah and Baruah 2011). Both systems,  $M_L$  and  $M_w$ , result in the same value for magnitudes between 3 and 5. For magnitudes less than 3, the scaling can be empirically derived as  $M_L \sim 1.5 M_w$  in some areas (Bethmann , Deichmann and Mai 2011). In this study, the moment magnitude ( $M_w$ ) was chosen based on the installed microseismic system records.

The average local magnitude can vary significantly in underground mines due to the local geology and extraction ratios. The average local magnitude of mining-induced seismic events is much less than 2.0, and these are categorized as microseismic events (Spence, Sipkin and Choy 1989). A rockburst is any seismic event from which the resulting seismic wave damages the mine openings, regardless of magnitude. Seismic events with  $M_L > 2$  or  $M_w > 1.3$  are typically referred to as "major seismic events" and can be heard and felt for large distances (up to 1500 m) in hard rock mines, but they are typically far enough away from excavations that no damage occurs (Kamie et al. 2015; Blake and Leighton 1971).

Seismic waves propagate through an elastic body in two main forms, as body waves and surface waves. Body waves travel directly through the elastic body, as opposed to surface waves which refract along the surface. Body waves are of the most interest to studies of induced seismicity in the underground environment. The travel rate of body waves through the earth is termed the seismic velocity. Body waves have two components of motion, compressional, (referred to as p-waves) and transverse (referred to as s-waves). P-waves have the highest velocities and are typically the easiest to identify by way of arrival times at sensors. The velocity of wave propagation is related to rock mass properties such as elastic modulus, shear modulus, density and Poissons's ratio (Keary, Brooks and Hill 2002) as shown in Equation 4-1 for P-wave velocities:

$$v_p = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}$$
(1-4)

Where E is Young's modulus, v is Poisson's ratio,  $\rho$  is density and  $\mu$  is shear modulus. Laboratory experiments on different rock samples show seismic velocity increases as applied stress rises (Scott et al. 1994; Khaksar, Griffiths and McCann 1999; He et al. 2018). Similarly, field scale analysis demonstrates that areas with higher velocity generally correspond to higher stress concentrations (Kerr 2011; Westman 1993). Additionally, high seismic velocity can reflect the increased stiffness of the local rock mass (Kerr 2011). Depth also increases seismic velocity by increasing the confining stress (Jones and Nur 1983).

## 4.4 Seismic Tomography

Induced seismicity within the rock mass can be used as an input for passive seismic tomography in order to image the distribution of the body wave velocity throughout the rock mass, and thus the stress distribution can be inferred. Passive seismic tomography uses the same computations as CT scan machines, which are used in medical imaging, to image the underground rock mass based on the recorded body waves propagated from seismic events (Westman 2004; Luxbacher et al. 2008; Ghaychi Afrouz and Westman 2018). With a microseismic monitoring system made up of multiple sensors installed in the rock mass, the seismic events can be recorded and their locations determined (Westman 2004; Wesseloo and Sweby 2008; Molka 2017). Velocity tomograms are, therefore, velocity variations in different cross-sections throughout the rock mass, calculated based on the seismic wave travel time along a ray path. Figure 4-1 schematically shows the tomograms within a rock mass calculated based on the travel time of the rays received by sensors.

Each major seismic event may result in a rockburst; therefore, the assessment of velocity variations before a major event can help to identify and perhaps define precursory rock mass changes indicating that a major event is imminent. Once the velocity variations are identified, an operation could then adapt current mining operations in order to reduce the exposure of miners to rockbursts. Prior to failure within the rock mass, the seismic velocity

typically increases due to the closure of existing cracks and pores in the rock mass, corresponding to the intensifying stress (Wyllie, Gregory and Gardner 1958; Thill 1973; Toksoz, Cheng and Timur 1976; Seya, Suzuki and Fujiwara 1979; Young and Maxwell 1992; Luxbacher et al. 2008). Acoustic experiments in the laboratory show that shortly prior to rock failure, the volumetric and circumferential velocities decrease despite the increasing stress. The rock may exhibit an abrupt, brittle failure or it may fail more gradually and in a ductile manner (Thill 1973).



Figure 4-1. Schematic display of seismic tomography in underground rock mass. The seismic rays propagate from a major seismic event, pass through the rock mass and are received by sensors. The velocity of other points within the area covered by rays are calculated based on velocity of the received rays.

The background velocity level for a rock mass is calculated as the average velocity for all of the rays that propagate through the rock mass. The area with a velocity that is higher than the background level is termed a "high-velocity zone". High-velocity zones exist either due to a different geologic material or due to induced stress; if the magnitude and distribution of the high-velocity zone changes with time then it is assumed that the zone is due to induced stress. Major seismic events potentially occur in or near high-velocity zones. High- and low-velocity zones may be present in the vicinity of each other (Ma et al. 2016).

# 4.5 Monitoring of In-Mine Seismicity

Microseismic monitoring is widely used in underground mining as a helpful tool to better understand mining-induced seismicity (Keary, Brooks and Hill 2002; Toksoz, Cheng and Timur 1976; Seya, Suzuki and Fujiwara 1979). Monitoring of microseismicity at mines involves different methods using surface or underground arrays (Swanson, Boltz and Chambers D 2016). The sensor types and locations should be selected based on the expected event magnitudes that a mine operator wishes to record. Underground arrays can cover lower-magnitude events in three-dimensional volumes of interest. A seismic network that includes underground arrays coupled with surface sensors is the most appropriate system for monitoring the induced seismicity surrounding mining sections (Swanson, Boltz and Chambers D 2016). Underground stress identification based on wave velocity has been commonly applied in deep mines, initially based on acoustic wave analysis (Young and Maxwell 1992). For many years, transducers have been mounted in underground mines, and later surface mines, to determine the failure mechanisms and rockburst hazards (Luxbacher et al. 2008) which can occur in progressive, continuous, or episodic patterns (Ma et al. 2016).

Several studies examined rock mass seismicity monitoring to better understand and predict rockbursts (Blake and Leighton 1971; Blake and Hedley 2003; Dehn and Knoll 2013). Cai et al. (2001) successfully quantified the fractures and cracks distributions using microseismic data. Based on their study, tensile cracking is the main factor in stress-induced fractures in the rock mass near an underground opening, which is in contrast to the mechanism observed for natural earthquakes which act along pre-existing faults (Cai et al. 2001). Luxbacher et al. (2008) were the first to use time-lapse, three-dimensional passive seismic velocity tomography to monitor the movement of high stress zones in a longwall panel (Luxbacher et al. 2008).

Some researchers introduced statistical analysis of major seismic events, such as Gaussian process, inversion and neural network techniques to predict rockbursts based on the pattern

of seismic event occurrence (Beer 2000; Jha and Chouhan 1994; Guo-Shao, Ke-shi and Zhi 2009). Ma et al. (2018) analyzed temporal b-value changes associated with mining-induced seismicity. Based on their observations, the b-value changed before each mainshock.

Although long-term rock mass failure trends help to recognize the pattern of the rock behavior in order to predict potentially hazardous reactions to induced stress, continuous monitoring is more helpful in the mining environment as the induced stresses are changing frequently. Numerous studies have investigated time-dependent seismic monitoring (Urbancic and Trifu 2000; Xu et al. 2011; Feng et al. 2015; Farzampour et al. 2019). Feng et al. (2017) present a warning method for rockburst monitoring systems in mines based on released energy ratio, shear component of the moment tensor, and P-wave development in order to first characterize the type of failure and then estimate the probability of failure (Feng et al. 2017).

The goal of the mining engineering discipline is to design systems that are safe, efficient, and environmentally responsible. To successfully accomplish this goal, we must first understand the behavior of the system. Seismicity is one of the least-understood aspects of deep mining and we must improve our understanding of the mechanics of the rock mass before we can engineer an improved system. Specifically, we must fully understand the behavior of the rock mass at the hypocenter of the seismicity prior to the occurrence of the seismicity. What is needed is a tool for underground mines comparable to slope stability radar used in surface mines, i.e., a real-time three-dimensional method for monitoring changes within the rock mass, thus allowing an improved understanding of the fundamental mechanics associated with induced seismicity, and specifically whether the P-wave velocity at the hypocenter increases in the weekly intervals prior to a significant seismic event.

## 4.6 Study Site and Seismic Data Set

In order to determine whether the P-wave velocity increased consistently prior to the three major seismic events in 2016, data was used from a deep, narrow-vein mine in the western United States. The mine is located in the Coeur d'Alene district which is comprised of different metasedimentary formations categorized as the Belt Supergroup. The central and western regions of the district include the Lower Belt, the Ravalli Group, the Middle Belt carbonate interval, and the Missoula Group. The Lower Belt hosts deposits of copper sulfide and the intruding veins are massive siderite and quartz (Harrison, Griggs and Wells 1974). The width of the veins does not exceed four meters. The silver ore deposits in the area are approximately parallel to veins trending N 65° W (Dehn and Knoll 2013; Fryklund 1964; Crosby1984). Due to alteration and partial oxidation, some addition of siltite, argillite and serictic quartzite is located in the belt formations (Mauk and White BG 2004).

Strong folding and syndepositional faulting affected the host rock which was intruded by several metal-rich veins. The mine is between two major right-lateral strike-slip faults which dip steeply and strike WNW. The vein as the mining target intercepts the major faults and their other subparallel offsets. The principal stress in the area is approximately parallel to the strike of the major faults (Dehn and Knoll 2013; Mauk and White BG 2004).

A catalog of 12,026 seismic events within an active mining section, recorded over the period of one year, was provided from the mine. The mine has used a microseismic monitoring system since 1968 (Blake and Hedley 2003; Blake and Leighton 1971). The current system is an ESG Paladin microseismic monitoring system consisting of 50 sensors, including 30 V/g and 40 V/g uniaxial accelerometers, 15-Hz triaxial geophones, and three strong ground motion triaxial geophones (Dehn and Knoll 2013). Figure 4-2 shows the event locations (red) and the sensor locations (blue) relative to development levels and ramps., along with the mine levels and access ramps between them for the active mining areas between 200 and -750 m mean sea level. The overburden depth is about 1,000 m above the area of interest. The entire seismic array encloses the majority of the active mine

workings which have followed large linear fault structures both along strike and along dip, resulting in a laterally oriented elongate ellipsoid.



Figure 4-2. Events (shown in red) and sensors (shown in blue) distribution along the mine opening, occurring in the active mining area. The side views of the active mine openings (in gray) are shown along easting and northing directions.

The active mining section targeted for this study is located at the northwestern end of the covered volume in areas that historically have been very seismically active, have a high extraction ratio, and represent good three-dimensional coverage by the seismic monitoring system. For reference, the area of the study is referred to as the Argentine. A close-up of the Argentine area is shown in Figure 4-3. The volume of the study area is approximately 275 m vertical by 700 m horizontal and 250 m wide. Mining during the study period only occurred in the central area of the volume, extracting a remnant pillar 20 m in vertical height and 150 m in length.

The red markers in Figure 4-3 are the seismic events recorded in the area. The events create a clustered cloud around the active mining, and the extents of the cloud are strongly constrained by geologic structures, mostly faults, but also by lithological contacts. The large size of the point cloud relative to the small remnant pillar indicates that the entire area was highly stressed.



Figure 4-3. Events locations along the active mining section (shown in red). The side views of the mine opening (shown in gray) are shown along easting (in left) and northing (in right).

The background average velocity of the seismic wave through the rock mass in the Argentine area is approximately 5,740 m/s (18,832 ft/s) based on the slope of the linear regression of the travel times of the events versus the travel distance. This method has been used in several studies to compute the background average velocity (Kerr 2011; Westman 1993; Westman 2004; Luxbacher et al. 2008; Molka 2017). Figure 4-4 shows this relationship in which the travel time of the seismic wave radiated from an event approaches zero as it becomes closer to a sensor. The standard deviation of the velocities of all seismic events in this area is 176 m per second. The scattered part of the graph at an approximate travel time of 0.25 seconds may indicate low velocity volumes (sand backfilled zones) around which the ray has refracted, or it may indicate an error in the data files.



Figure 4-4. Average velocity of the area, which is equal to 5,740 m/s (18,832 ft/s), calculated from the inverse slope of the travel time to the distance. The standard deviation of the average velocity is 176 m/s for all the events recorded in the area.

The 12,026 seismic events resulted in more than 130,000 recoded travel times from the monitored seismicity. The total number of the received travel times for the target active mining section was calculated for weekly intervals as shown in Table 4-1. Figure 4-1 shows the cumulative number of events by day throughout the year as well as the cumulative energy release during the year. It can be observed that three major events occurred during the year and that with each of them the seismicity rate had an associated increase. By comparing Table 4-1 and Figure 4-5, it can be seen that the three major events occurred during the weeks that had the most travel times recorded.

Table 4-1. Number of recorded travel times per week





Figure 4-5. Cumulative released energy and cumulative number of events (top) in a year of operation compared to the moment magnitude of those events (bottom). The blue line shows the cumulative released energy (J). The three major seismic events are indicated by dashed black lines where the cumulative released energy has the most significant increase.

## 4.7 Methods and data analysis

Each velocity tomogram shows the calculated velocity distribution during the specific time frame of data. Longer time intervals will have a greater number of travel times so that the velocity distribution can be obtained with greater resolution. Monthly, weekly, daily, or even hourly tomograms can be produced based on the number of travel times available and the need of the study to determine the effect of a major seismic event. Monthly velocity tomograms were initially analyzed for this data set, but these results showed very little fluctuation associated with the major events. Therefore, weekly tomograms were calculated, which made the velocity fluctuation more apparent and useful for analysis while still maintaining an adequate number of data points per time period. Using one-week of data for each tomogram assured that the velocity calculated for each voxel within the primary area of interest would be determined based on at least 10 p-waves traveling through that voxel.

After identifying the major events, called Event 1, Event 2 and Event 3, which had moment magnitudes of 1.62, 1.81, and 1.75 respectively. The ratio of shear-wave energy to P-wave energy for the three events was 4.86, 2.95, 3.47, respectively while the average for all events recorded during the year was 4.42. If the failure mechanism was purely shearing, then it would be expected that these ratios would be significantly higher than the average for all events. Tomograms were created to determine the seismic velocity changes in the vicinity of these major events. To calculate the tomograms, the area of interest was divided into a fixed, consistent number of voxels. A voxel size of 29 m (95 ft) per side was used for this study. The volume of interest exists within a rectangular cube measuring 40 x 150 x 40 voxels in the northing, easting, and elevation directions, respectively. This size was used because it ensured that at least 25 rays traversed each voxel within the area of interest. Figure 4-6 shows the voxel locations used to compute tomograms. The Fast Marching Method allows curved ray propagation and was used for ray tracing while the Simultaneous Iterative Reconstruction Technique was used for tomographic inversion. The initial velocity model was set to the average velocity of 5740 m/s (18,832 ft/s) uniformly for the

entire model. The optimal result was chosen as the iteration identified with the elbow method for the graph of the root mean square of the residual of the ray path travel times in each iteration (Ketchen and Shook 1996; Bholowalia and Kumar 2014). The elbow is picked based on the intersection of the perpendicular line from the tangent's intersection point to the graph as shown in Figure 4-6. Based on this method, the optimum iteration number for this study was consistently 10 for all of the weekly data sets. The resulting voxel locations and their respective calculated velocities were then input to a volumetric visualization software and interpolated using the inverse distance method to the first power.



Figure 4-6. Side view of voxel spacing (red dots) along the area of interest (the gray lines) and sensor locations (blue squares) along the area.



Figure 4-7. Optimum number of iterations based on the elbow method based on graphing the root mean square of the residual of the ray path travel times in each iteration. The 10th iteration has the optimum velocity calculated for each voxel.

Weekly velocity tomograms were generated for a total of nine weeks, the four weeks before, the week of, and the week following each of the major events. The weekly time intervals were selected based on the date of the occurrence of each major seismic event. For the time interval that contained the major seismic event, the weekly time period began at 12:01 AM the day that the major event occurred; remaining time intervals were then determined based on that time period, hence the tomogram for the week prior to a major seismic event includes data for the seven-day period that ends at 11:59 PM the day prior to the occurrence of the major event. It is important to note that Event 3 occurred 17 days following Event 2 and so there is overlap in the results for the two events.

In addition to analyzing velocity change at the hypocenters, a method from slope stability monitoring at surface mines was adapted. Slope stability radar (SSR) detects rock slope failure based on displacement graphs. SSR is based on the wavelength difference of the sent and received radar wave, which can measure the displacement of the rock slopes toward the reflection point. Using this technique, wherever the displacement gradient is higher than the background level of deformation for each pixel, the pixel will be marked as the potential for the slope failure. Increases in the number of the marked pixels and/or the acceleration in the average accumulative displacement of all marked pixels are the precursors for a rock failure in that area (Harries and Roberts 2007; Harries and Holmstorm 2007). In much the same way that SSR identifies "zones" of high displacement, in this study, the authors identified "zones" of high velocity in the tomograms and then analyzed changes to those zones to determine whether there was any significant change in them related to the occurrence of the major seismic events.

High-velocity areas, interpreted as being associated with a volume of increased stress, consisted of voxels with average velocities higher than the background velocity level of 5,740 m/s (18,832 ft/s). Plotting of the velocity distributions in three-dimensions for the four weeks prior to each major event identified three high-velocity zones. These zones are located between -120 and -215 m (-400 and -700 ft) in elevation and are clustered around the active working areas. The voxels located at the center of these zones have a velocity of

higher than 6,460 during weekly intervals before and after each event. The higher-velocity limit of 6,460 m/s (21,200 ft/s) was used to better define the extents of the high-velocity zones and determine their geometric centers. The higher-velocity zones, termed Zones A, B, and C, along with the hypocenters of three major seismic events, are shown in Figures 4-8 and 4-9.

### 4.8 **Results and Discussion**

#### 4.8.1 Tomograms

In order to analyze changes to the P-wave velocity distribution, indicating changes to the induced stresses, in the rock mass within the immediate vicinity of the three major seismic events, a section plane was aligned with the actively mined vein, both parallel to it and with no offset. The section plane passed within 18 meters of Event 1's hypocenter, 3 meters of Event 2's hypocenter, and 10 meters of Event 3's hypocenter. The plan view and side view of the section plane with the high-velocity zones for the two weeks preceding Event 1, as a typical example, are shown in Figure 4-8 and 4-9, respectively.

Only Zones A and C intersected the section plane, and their resulting velocity variations are shown on the tomograms in Figures 10 to 12, chronicling the four weeks before and after each major seismic event. Zone B is not projected on the section plane. In the tomograms, Zone A is located near the upper left of each tomogram and Zone C is located near the center. Spatially, Zone C is located in the footwall of the vein and is associated with a zone of complex intersecting geologic structures. Locations of the three major seismic events, which did not all occur along the section plane, are shown with red squares and labeled with their identification number.



Figure 4-8. Plan view of the cross-section intersecting with three high-velocity zones in the two weeks prior to Event 1



Figure 4-9. Side view of the cross section intersecting with three high-velocity zones in the two weeks prior to Event 1



Figure 4-10. Velocity tomograms for four weeks before and after Event 1. Zone A is located in the upper left side of the tomogram and Zone C is located in the center, the hypocenter of Event 1 is indicated by a red marker located between the two high-velocity zones. The average velocity in Zone A decreases noticeably after the event.


Figure 4-11. Velocity tomograms for four weeks before and after Event 2. Zone A is located in the upper left side of the tomogram and Zone C is located in the center, the hypocenter of Event 2 is indicated by a red marker located between the two high-velocity zones. Due to the timing of Events 2 and 3, the tomogram labeled "Post Event 2 – two Weeks After" corresponds to "Prior to Event 3 - Week of Event 3" in Figure 4-12.



Figure 4-12. Velocity tomograms for four weeks before and after Event 3. Zone A is located in the upper left side of the tomogram and Zone C is located in the center, the hypocenter of Event 3 is indicated by a red marker located between the two high-velocity zones. Note that velocities in Zone A decrease noticeably four weeks after Event 3. The tomogram three weeks before Event 3 includes the energy release of Event 2.

The velocity distributions generated for the weekly intervals display several consistent results. First, it is observed that although each of the tomograms was generated from a unique data set, there is a general level of consistency in the results from the different weekly periods; the location and magnitude of the elevated velocity regions are generally

consistent. Zone A is located at the upper left side of the area of interest (i.e. to the west and lower elevation) and Zone C is located at the center of it. Second, the three major events each had a hypocenter that was located in an area that was associated with elevated velocity, but not in the area with the highest velocity; in other words, the three hypocenters are each located that corresponds with inferred high stress, but on the boundary of the inferred highest stress, not in the middle of it. This observation is consistent with conventional fracture mechanics where it is understood that fractures form on the boundary of highly-stressed zones, not within the most highly-stressed locations (Bunger, Jeffery and Detournay 2005). The third observation is that there is no immediately obvious increase in velocity at either the hypocenters or the zone centers prior to the major events at the scale of this study (29 meters between voxel nodes). Because a readily observable increase in velocity was not observed from the results plotted on the section plane, the results were plotted as line graphs showing weekly velocity changes within a specific volume surrounding the hypocenters and zone centers in order to determine if more subtle velocity increases prior to each seismic event were present.

In order to more closely examine velocity changes within specific volumes the average seismic velocity of all voxels located within 45 m (150 ft) radii from each major seismic event hypocenter and the zone centers was plotted for the 4-week intervals before and after each event. The 45 m radius was selected based on the edge length of each voxel. This analysis provided a means for monitoring the seismic wave velocity changes in the immediate vicinity of the major events. Figures 4-13 to 4-15 display the velocity changes for the corresponding time period along with the cumulative released energy and the cumulative number of events recorded throughout the mine. For all areas analyzed, the average velocity for the analyzed values was greater than the background velocity level.



Figure 4-13. Velocity changes prior to and following Event 1, The hypocenter of Event 1 shows no increase within two weeks of the occurrence of the event the velocity of Zone A shows a slight decrease prior to the event occurrence.

The average seismic velocity within a 45 m radius of the hypocenter of Event 1 shows does not increase in the week prior to Event 1, and a very minor decrease in velocity for the five weeks prior to the event. The average velocity associated with Zones A exhibited a larger magnitude decrease in velocity during the week preceding the event.



Figure 4-14. Velocity changes prior to and following Event 2. There is a gradual decrease in average velocity near the hypocenter of the event and Zone A is more influenced by the occurrence of the event. Event 3 occurs at day 217.

Seismic velocity near the hypocenter of Event 2 decreases in the week prior to the event and is lower in the week prior to the event than it was four weeks earlier; following the event the velocity increases to the pre-event levels. As noted earlier, Event 1 and 2 are temporally separated by five months, providing ample time for the area to reach a new equilibrium after Event 1, however Event 3 is only 17 days after Event 2 and so the rock mass response may be affected by the interaction between the two events whereas Event 1 was isolated from other major events. Zone A has an abrupt increase in velocity before Event 2 and an equal decrease afterwards.



Figure 4-15. Velocity changes prior to and following Event 3. The average velocity at the hypocenter of the event is slightly influenced by the event occurrence, Zone C has the most changes before and after the event occurrence, at day 250 new mining activities began at deeper elevations.

The average seismic velocity near the event hypocenter of Event 3 is higher than the background velocity level, similar to the two other events. Zone C is closest to Event 3 and there is an increase in velocity for the four weeks prior to the event, continuing for several weeks after the event. The velocity change associated with the volume near the hypocenter showed little change during the weeks prior to Event 3, there is a very small (52 m/s, 0.8%) decrease in velocity for the week before the event.

Figures 14-3 to 4-15 also show cumulative energy and cumulative number of events. Major events can be recognized as significant increases in the accumulated released energy. As can be seen, the cumulative released energy is correlated to the occurrence of the significant

events as they result in step increases to the cumulative released energy. In addition to the cumulative released energy, the cumulative number of events is also shown on the figures. There is a change in the slope of the graph of the cumulative number of events after the occurrence of each of the three major events. As an example, prior to Event 1 approximately 30 events per day were typically recorded; however, after Event 1 the rate increased to more than 150 events per day. This means that after each major event, the frequency of minor events changes. This is more noticeable for Events 1 and 2 than it is for Event 3.

The objective of this study has been to determine if the P-wave velocity increases prior to major seismic events. A continually-increasing stress would be recognizable by an intensifying high-velocity zone prior to the occurrence of each of the three major events. However, this was not observed at any of the three hypocenters. Only Event 1 shows a very subtle increase around its hypocenter (13 m/s, 0.2%) and the other two events show an increase in the average velocity in the vicinity of the hypocenter. In addition to the hypocenters, the P-wave velocity was also examined for 'zones' of interest. For two of the three events the velocity increased prior to the seismic event; however, further analysis would need to be conducted with additional data sources to determine whether this is a repeatable trend.

An alternative hypothesis that could be considered is that the increase in P-wave velocity due to increasing induced stress prior to a major seismic event may be canceled due to the formation of new fractures in the rock mass as the ultimate strength of the rock mass is approached. In the absence of the persistent build-up of stress before the occurrence of major events, it can perhaps be expected to observe a dilation due to propagation of the fractures in the rock mass, resulting in a decrease of seismic velocity. For two out of the three events the seismic velocity at the hypocenters decreases within a week of the occurrence of the event.

When analyzing data in one-week intervals the rock mass does not show the hypothesized trend of increasing P-wave velocity prior to a major event. Future studies, however, should

be conducted to determine whether there are changes in the P-wave velocity distribution associated with significant seismic events at different time intervals, for example using a rolling three-day average. Additionally, future work could analyze the accuracy of the results through statistical methods such as bootstrapping.

## 4.9 Summary and Conclusions

The P-wave velocity distribution at a deep narrow-vein mine was calculated for weekly time intervals in order to test the hypothesis that the induced stress near hypocenters of major seismic events increased continually. The passive seismic tomography data analysis over a year of operation around an active mining section showed consistent results for weekly, unique datasets. Three major seismic events occurred during the year that was analyzed and the P-wave velocity did not increase in the vicinity of the hypocenter for any of the three; for two of the events the velocity deceased in the week prior to the event (by 2.1% and 0.8%) and for the third event the velocity was essentially unchanged from the week prior. Based on this analysis, the hypothesis that the P-wave seismic velocity would continually increase at the location of the eventual hypocenter is not accepted for these events at this mine. A potential reason that the hypothesis was not supported by the data is that new fractures may be developing within the highly-stressed rock mass, resulting in either no increased velocity or a reduction in velocity at the hypocenter prior to the seismic event.

In addition to analysis at the hypocenters, three 'zones' of high velocity were observed around the active mining area. This analysis was conducted as an analog to slope stability monitoring with radar, which analyzes zones of high movement. The high-velocity zones were generally consistent in location and magnitude for the weekly data sets however there were changes before and after each event in terms of the volumetric extent as well as the peak magnitude. Two of the high-velocity zones increased in average velocity the week before the seismic event (one by 3.4% and the other by 0.8%) while the third saw a decrease

of 2.6%. Additional case studies are required to determine whether the results observed for these three events also occur at other times and other deep mines.

A secondary observation is that the hypocenter of all the three major events occurred at the edge of the high-velocity zones rather than at the center of the zones. This may be due to higher deviatoric stress levels near the edges of the zones, which allow the deformation of the rock mass, as compared to the center of the zones, which likely have a higher degree of a more uniform stress field. Therefore, when observing a high-velocity zone in tomograms, there is a strong potential for the subsequent event to locate somewhere along the edges of the zone.

The pattern of energy release was different in each of the three events, which may be due to the different failure mechanism (which this study did not investigate). Events 1 and 3 occurred suddenly followed by several minor events, while Event 2 triggered fewer subsequent minor events but was followed by a major event 17 days later.

Induced stress measurement is one of the challenging tasks in deep underground mining, impacting the safety and stability of the mine tremendously. This study used P-wave passive seismic tomography to image the velocity redistribution within a rock mass, which can indicate induced stress level changes in the rock mass and detect the velocity changes that might precede a major seismic event or a rockburst. The ultimate goal of this research focus is to develop another tool for the deep mining community that will help to increase safety and efficiency.

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# Chapter 5 - Underground rock mass behavior prior to the occurrence of mining induced seismic events

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## 5.1 Abstract

The variations of seismic velocity prior to the occurrence of the major seismic events are the indicator of the rock mass performance subjected to mining induced stress. Monitoring these changes is critical for mine stability and operation safety and eventually improves production by optimizing mine designs and mining practices. The "daily velocity difference" is the variations of the seismic velocity of each point in two consecutive days computed by the seismic tomography algorithm. In this study, five seismic events that occurred in a narrow vein mine were considered as case studies and the daily changes in their seismic velocity within a week of event occurrences were evaluated. The data were recorded by 50 sensors mounted in the mine tunnels during a year. It was observed that the velocity difference of the day of the event occurrence increased significantly compared to the subtle changes on previous days. Additionally, the influence of blasting in the week of the occurrence of events were investigated; however, no recognizable trend was observed between blasting and seismic velocity of the rock mass on the day of blast or its following day.

# 5.2 Introduction

Mining activities change the stress equilibrium in the underground rock mass by applying induced stress on the mining abutment rock mass. Seismic events, rockbursts, and bumps are the rock mass response to gain back its equilibrium in deep underground excavations (M. He, Ren, and Liu 2018). The stability of the excavation can be increased through

continuous monitoring of the induced stress and mitigating the potential of rockburst occurrence. Variations of the applied stress in the underground rock mass can be investigated based on the variations in seismic wave velocity propagations, which technically are velocities of compressive ( $V_p$ ) and shear body ( $V_s$ ) waves passing through rocks (Zhao and Zeng 1993). Experiments on rock samples showed a correlation between applied stress and P-wave velocity (Thill 1972; He et al. 2018). Additionally, field studies found that the seismic velocity of the area is relatively high in encompassing rock mass when major seismic events occur (Luxbacher, Westman, and Swanson 2007; Ghaychi Afrouz and Westman 2018; Barthwal and van der Baan 2018; Westman et al. 2001). A seismic ray is the path of the propagated seismic wave which is received by sensors (Aki and Richards 1980). Passive seismic tomography is a technique through which the seismic wave velocity in the underground can be modeled and its changes by time can be monitored (Terada, M.; Yanagidani, 1986; Westman, 2004).

Usually, rockbursts are accompanied by several smaller seismic events, which can be detected by seismic monitoring networks (Luxbacher et al. 2008). Major seismic events have been monitored in deep mines with regional mine seismic networks for a long time (Westman et al. 2001; Mendecki, 1996). In some cases, it was observed that the seismicity in the underground rock mass increases prior to occurrence of rockburst, however, not all rockbursts are associated with minor seismic events prior to the occurrence of the burst (Ellenberger and Engineer 2000). The moment magnitude of rockbursts differs from 3 to 5 while major seismic events have moment magnitude between 1 and 3. A mine-scale seismic monitoring system, called a microseismic system, including geophones encompassing the mining excavation and can record the seismic waves propagated from any seismic event even if they are as minor as -2 Mw (Foulger et al. 2018; Blake and Hedley 2003). Regional seismic systems were first applied in coal mines to calculate the locations of seismic events based on the travel time of the recorded seismic waves (Mendecki 1987; Mendecki 1996).

The volume of interest is divided into smaller cubes, called voxels. The seismic velocity of each voxel can be estimated based on the arrival time of the recorded seismic rays propagated from each seismic event with passive seismic tomography (Westman et al. 2001; Westman 2004). This method has been applied in longwall coal mining to monitor the seismic velocity changes correlated to variations of induced stress during the mining operations (Luxbacher, Westman, and Swanson 2007; Luxbacher et al. 2008). Primarily, the characteristics of petroleum reservoirs due to the fracturing procedure were monitored by passive seismic systems (Zhang et al. 2009; Rutledge, Phillips, and Schuessler 1998; Rutledge and Phillips 2003; Maxwell, Du, and Shemeta 2008). Later it was applied in deep hard rock mines to identify the highly stressed areas and monitor the corresponding induced stress redistribution (Ma et al. 2018; Ghaychi Afrouz and Westman 2018; Zhang et al. 2009; Ma et al. 2019a). The passive seismic tomography was used to evaluate the destressing and stressing of damaged zones surrounding underground tunnels (Barthwal and Van der Baan 2018).

According to laboratory experiments on rock samples, the body wave velocity increases correlating with the increase in compressive stress (Scott et al. 1994). This increase in seismic velocity continues until the cracks formation and propagation are in progress before the applied stress reaches to its peak. When the cracks merge and the dilation begin, the body wave velocity slightly decreases (He et al. 2018). After this retrograde point, the body wave velocity increases again in parallel to the loading direction (He et al. 2018). In the field scale, the seismic velocity increases by increasing the depth or decreasing the distance from the sources of induced stress, such as mining activity (Westman et al. 2001; Westman et al. 1994). It was observed that there are areas with higher seismic velocity than the average seismic velocity of the rock mass at a particular depth, called background seismic velocity. The locations of these high-velocity zones are in the vicinity of the mining locations and have high seismicity (Luxbacher et al. 2008; Westman et al. 1994).

In this study, we investigated the changes in the seismic velocity of the rock mass prior to the occurrence of major seismic events in two active mining sections at a narrow-vein mine. It was anticipated to observe built-in stress in the rock mass due to the accumulation of the induced stress in the area. Therefore, the velocity difference might increase in days before the major seismic event occurrence. This hypothesis was investigated by evaluating the daily changes of potential high-velocity zone in the vicinity of the hypocenter of events before the event occurrence. The seismic record of the mine during a year of operation showed five major events with high released energy and high magnitude. Passive seismic tomography was used to back analyze the daily seismic velocity difference in the surrounding rock mass within a week of the occurrence of the major seismic events in one of the mining sections was explored as well. The goal of this study was to evaluate if there is any observable change in seismic velocity of the surrounding rock prior to the occurrence of seismic events as an indicator of mining induced instabilities.

# 5.3 Data and Methodology

This study was based on the data of a mine located in the western U.S.A, along a silverrich belt including several silver veins with lead and copper byproducts (Mauk and White 2004). The active mining sections studied in this research are along this belt. The dominant faults in the mining area are striking WNW. The narrow veins, with an average width of two to three meters, include the ore contained in the shear zones in between the faults. The veins are steeply dipped with various extensions from 90 m to 900 m (Dehn, Butler, and Weston 2018). The mining area includes a variety of weak to high strength rocks with anisotropy in the direction of the steep bedding planes (Chan, 1970.; Dehn, Butler, and Weston 2018).

The data for this study was recorded by an ESG Paladin data acquisition system comprised 50 mounted sensors in a narrow-vein mine with two active mining sections. The installed sensors consist of uniaxial accelerometers and triaxial geophones (Dehn, K.; Knoll 2013).

The mine openings and location of sensors installed in this mine are as shown in Figure 5-1. The seismicity in the two active mining areas during a year were analyzed separately. The seismic velocity tomography was used to investigate the rock mass behavior in these two active mining sections.

During a year of seismic monitoring, more than 12,000 seismic events were located in Mining Section 1 through more than 132,000 recorded seismic rays. This number is much higher in Mining Section 2 with more than 16,000 located seismic events through 172,000 recorded rays in a year. The background velocity of both sections is about 5,740 m/s.



Figure 5-1. Sensors distribution along the mine openings in two mining sections (top view and side views). Red points are the sensors and the gray lines are mine openings.

The events with the highest released energy, which indeed have relatively high moment magnitude, were chosen as the major seismic events. Five major seismic events were observed in the year of study. Figure 5-2 shows the cumulative energy and moment magnitude of all of the recorded events in both mining sections. The five major seismic events are marked in Figure 5-2. The event's labels are based on the mining section number followed by the event number in order, for example, Event 1-2 is the second event in Mining Section 1. The moment magnitudes are 1.62, 1.81, 1.75, 1.48 and 1.76 for Events 1-1, 1-2, 1-3, 2-1 and 2-2 respectively. The source locations of events and their magnitude and corresponding released energy were computed by ESG's Windows-based Hyperion Seismic Software (HSS) Suite based on P-wave and S-wave arrival times.



Figure 5-2. Cumulative released energy and moment magnitude of the recorded events in Mine Sections 1 and 2. The days of the occurrence of major seismic events are marked and labeled for each section.

According to Table 5-1, the moment magnitudes of each of five events is more than 1.4. The S-wave released energy of the two major events at Mining Section 2 is relatively much higher than their P-wave released energy, showing these two events are fault-slips type. The lower energy ratio of shear wave to compressive wave (Es/Ep) in Mining Section 1 can possibly be an indicator of rock bridges failure along existing discontinuities in this area rather than fault-slip.

Major Seismic Event		Day	Easting (m)	Northing (m)	Elevatio n (m)	Moment Magnitude	Released Energy (J)	Es/Ep
Mining	1-1	65	3434.94	2317.69	-149.58	1.62	2,270,000	2.95
Section 1	1-2	199	3428.81	2323.53	-214.16	1.81	2,970,000	3.47
	1-3	216	3428.17	2339.71	-175.96	1.75	1,870,000	4.86
Mining	2-1	33	2561.40	3631.27	-574.28	1.48	3,200,000	24.89
Section 2	2-2	248	2728.75	3563.59	-648.71	1.76	2,440,000	7.43

Table 5-1. Number of blasts per day within a week of event occurrence in Mining Section 1

The seismic tomography method was used to calculate the average velocity of highly stressed areas adjacent to active mining areas. The average velocity of each voxel was calculated during the different time-periods, such as 7-days or 24-hours. The accuracy of the calculation depends on the number of recorded seismic rays passing through each voxel

during a particular period. Therefore, larger voxels or larger timespans will include more raypaths. However, if the voxel size is very large then the results will be smoothed out. In this study, seven-day and six-day time spans were considered to have adequate ray coverage. The subtraction of two time spans, one of which including an additional day, indicated the seismic variations in the additional day. "Velocity difference" is defined as the difference in the seismic velocity of the two consequent time spans with overlapping days. In this study, for every day within a week of the occurrence of each event, the sevenday and six-day time spans were considered and their average velocities were subtracted. The result was the daily velocity difference within a week.

The daily velocity differences were graphed in three dimensions and compared with the blasting rate per day. The seismic tomography was based on the Simultaneous Iterative Reconstruction Technique (SIRT) algorithm (Trampert, Jeannot; Leveque 1990) which computes the total number of rays passing through each voxel through several numbers of iterations. The velocity of each voxel in each timespan was computed in different iterations. The root mean square of the residual travel time measured by sensors and calculated by tomography was calculated for each iteration. The elbow method was used to define the optimum number of iterations for the most accurate calculated velocities (Bholowalia 2014). In this study, the calculations at iteration number 10 were used. The tomograms of the velocity difference were estimated in three dimensions.

The boundary which confines the voxels with an adequate number of rays is considered as the "boundary of confidence". The minimum number of rays for the six-day time span among the five major events was 573 and the boundary of confidence was measured as 10. This means that voxels within this boundary had more than 10 rays and their computed average velocity had an error of less than residual at the optimum iteration (less than 0.1 sec for this study).

#### 5.3.1 Blasting

The time and location of blasts in Mining Section 1 were provided by the mine site. Therefore, the number of blasts per day were considered as an influencing factor regarding mining advance. The maximum two blasts per day started in the third quarter in the year of production. Two of the major seismic events occurred at this quarter. There is no blasting within days 130 to 178. The average advance rate of the year of study including the no-blast period is 1.7 meters per day.

Considering that the blasts within a week of occurrence of each event had the most influence on the surrounding rock mass behavior, the number of blasts in seven days prior to each major event are summarized in Table 5-2. There were at least three blasts within a week of occurrence of all three events. For example, "Day 0" is the day of the event and for Events 1 and 3 there are one and two blasts in each respectively. Figure 5-3 demonstrates the spacing of the blasts in the plan view and side view. It is observed that the blasts were in three different mining levels and proceeded from the highest level to the lowest.

Number	Days prior to the major event									
of blasts	-	-	-	-	-	-				
prior to	6	5	4	3	2	1	0			
Event 1-1	1	1	0	1	0	0	1			
Event 1-2	0	1	1	0	1	1	0			
Event 1-3	0	2	1	2	0	1	2			

Table 5-2. Number of blasts per day within a week of event occurrence in Mining Section 1



Figure 5-3. Plan view of the blast locations along with the mine maps(top) and side view of the blast locations in three levels (bottom).

# 5.4 Results

Passive seismic tomography was used to calculate the velocity of each voxel with a size of 29 m. The minimum difference between the measured velocity by sensors and the calculated velocities by the SIRT tomography algorithm obtained at the 10th iteration for both mining sections showed the residual of less than 0.1 sec. The tomograms of daily

velocity difference for all five events were calculated. Figure 5-4 and 5-5 show the vertical cutting section chosen for mining sections 1 and 2 respectively perpendicular to the main vein. The Euclidian distance between the hypocenter of the major events and their cutting section is less than 10 m. As the distance between Event 1 and Event 2 in Mining Section 2 is 195 m, two parallel cross-sections are considered for demonstrating the seismic velocity at these events. Figure 5-5 shows these two cutting planes intercepting the mine opening in Mining Section 2. The planes are dipping North-East. There is a 60 m distance between these two parallel planes.



Figure 5-4. Location of Hypocenters of the three events at Mining Section 1 regarding the cutting plane in three dimensional view (right) and plan view(left)



Figure 5-5 Location of Hypocenters of the two events at Mining Section 2 regarding the cutting planes in three-dimensional view (right) and plan view(left)

The daily velocity differences for the events that occurred at Mining Section 1 were compared at the shown cutting sections within a week prior to each event. The boundary of the 10 rays per voxel for the accuracy of the calculations was provided as well. The blasting locations for this mining section were recorded and provided by the mine engineers. The same comparison was accomplished for Mining Section 2; however, the locations and times of the blasts in this section were not provided. The tomographic images of velocity differences in a week prior to event combined with the blasting locations in each day and the boundary of confidence of 10 rays per voxel are shown in Figures 5-6 to 5-8 for Mining Section 1. The velocity differences of the two events in Mining Section 2 are shown in Figures 5-9 and 5-10. As the locations of the blasting in this area are not provided, these images do not include the blasting data. The crossing mine openings are shown in light gray lines.



Figure 5-6. The daily velocity differences from six days prior to Event 1 at Mining Section 1. The boundary of confidence with 10 rays per voxel for each day is shown in black and the days with blasting are marked with the location of the blast. The blast locations are within 30 m of the hypocenter.



Figure 5-7. The daily velocity differences from six days prior to Event 2 at Mining Section 1. The boundary of confidence with 10 rays per voxel for each day is shown in black and the days with blasting are marked with the location of the blast. The blast locations are within 30 m of the hypocenter.



Figure 5-8. The daily velocity differences from six days prior to Event 3 at Mining Section 1. The boundary of confidence with 10 rays per voxel for each day is shown in black and the days with blasting are marked with the location of the blast. The blast locations are within 30 m of the hypocenter.



Figure 5-9. The daily velocity differences from six days prior to Event 2 at Mining Section 2. The boundary of confidence with 10 rays per voxel for each day is shown in black and the days with blasting are marked with the location of the blast. The blast locations are within 30 m of the hypocenter.



Figure 5-10. The daily velocity differences from six days prior to Event 2 at Mining Section 2. The boundary of confidence with 10 rays per voxel for each day is shown in black and the days with blasting are marked with the location of the blast. The blast locations are within 30 m of the hypocenter.

## 5.5 Observations and discussions

Passive seismic tomography can model the velocity of different voxels of rock mass in a designated time-lapse. The performance of the rock mass to the occurrence of five major mining induced seismic events was investigated with the week of event occurrences. The daily velocity difference at the day of occurrence of events (day "0") to the previous days showed that major seismic events increase the seismic velocity difference of the rock mass at day "0".

According to Figures 6 to 10, the velocity difference of the five events is changing daily as it gets closer to the day of the occurrence of the major event. Moreover, tomograms show a velocity of higher than background velocity of 5740 for the majority of voxels within 200 m of the hypocenters of events. The dynamic changes in these high-velocity zones increases after day "-6". The maximum velocity of the voxels within 200 m from hypocenters increases from about more than 40 m/s from day "-6" to day "-5" or more than 1% increase in seismic velocity. The only exception for this jump is Event 2 in Mining Section 1 in which the increase was observed from day "-5" to day "-4". This high-velocity zone is as small as 2 to 5 voxels and not necessarily are intercepted by designated cutting sections. Therefore, in day "-5" compare to day "-6" just a subtle increase (less than 1%)in the velocity is seen at the cutting section 1 the increase in maximum velocity of voxels drops after the blasting on day "-5". The subtle changes can be due to the formation and extension of the cracks in the rock mass especially when the seismic event is not a shear dominant failure or a fault-slip such as event 2 in Mining Section 1.

The blasting does not influence the velocity difference in a predictable pattern. The increase in seismic velocity due to basting is not persistent in all three events. For example, in Event 1in Mining Section 1, a high-velocity zone is observed on the day of the blast at day "-5" but there was no noticeable change in seismic velocity in day "-3" with a blast in the same level. This might be due to a one-day break in blasting at day "-4" compared to

two continuous days of blasting. Blasting did not identically influence the velocity difference of the day after or the day of blasting. Nevertheless, all five events happened when there were at least three blasts within their occurrence. Moreover, during the week of occurrences of Events 1 and 3, some random high velocity zones were observed in a single day and vanishing in the day after. These scattered zones could be as a result of the blasting in the area, however there was not any persistent trend in their advent after blasting. For example, the high velocity zone at south east of the hypocenter of the Event 3 at day "-2".

On the other hand, the day of the event for all five events (day "0") the most difference was seen compared to the day -6 with the least velocity difference. Also, on the day of all of 5 events, which is day zero, the velocity of the area increases in larger volumes compared to even its previous days. The velocity difference at day 0 is more than 1% within 200 m of the hypocenter of events. In Mining Section 1, where Es/Ep of the events is less than 5, some changes subtle change in seismic velocity are observed. However, in Mining Section 2 where events have higher Es/Ep, there is no significant change in velocity prior to the event occurrence. This changes in day of the event occurrence compared to a previous day (from "0" to "-1") is more noticeable for Event 2-1 with Es/Ep ratio of 24.89. The seismic velocity of all five events regardless of their shear dominance is higher than the average velocity. The fluctuations of the seismic velocity in a smaller scale can be investigated in further studies by analyzing the data in shorter time-lapses. This approves the literature finding were there were no significant changes in seismic velocity prior to major events but there might be some subtle fluctuations due to the dilation prior to maximum applied stress (Molka 2017).

#### 5.6 Conclusion and future work

In this study, the occurrence of five major seismic events in two mining sections in a year of is evaluated by passive seismic tomography to investigate the rock mass behavior prior to the occurrence of major events. The seismic velocity of the rock mass changes during this period and its changes were computed daily within a week of each event. It was observed that for three of the five events, there was no velocity change of more than 1% within 200m of the hypocenter 6 days prior to the event. However, the velocity difference was more than 1% within 200m of the hypocenter on the day of all five events. This means that seismic events cause a significant change in the stress level of the surrounding rock mass but without substantial change in velocity in days before. However, there were some gradual changes of less than 1% in seismic velocity in the prior days of the event occurrence. These subtle changes might be due to the dilation during the plastic failure of the rock mass.

The investigation of the blast rate in the three of the events with Es/Ep of less than 5, did not show any persistent trend in seismic velocity changes correlated with blasting. However, all these three events occurred with at least three blasts within a week of their occurrence. The random high-velocity zone could be induced and distressed after blasting but there is no predictable trend in their advent.

The minor changes in seismic velocity, which are less than 1%, can be investigated in future studies. The initiation of cracks which propagate and merge in the rock mass might be the cause of these changes in the rock mass. A reasonably predictable trend in seismic velocity changes can be a potential precursory condition for identifying major seismic events prior to their occurrence. This can be crucial for increasing the safety of the mines by taking advantage of seismic tomography.

Moreover, mining designs can be optimized if the rock mass performance is monitored by progress in mining. It is recommended for future studies to investigate the subtle changes in seismic velocity in order to identify the possibility of any limit that can be an alarm threshold for operating crews to halt mining and avoid highly stressed zones.

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# *Chapter 6* - Monitoring rock mass behavior at a deep narrow vein mine by seismic wave velocity variation graphs

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## 6.1 Abstract

Mining activities induce stress in the surrounding rock mass and typically result in several minor and some major seismic events. There is a relationship between major seismic event occurrence and seismic velocity variations in the abutment rock mass. The changes in seismic velocity are more severe in more vulnerable zones in the vicinity of the major events which could be monitored in proper time spans. According to laboratory experiments and numerical analysis, the seismic velocity decreases prior to the occurrence of the major seismic events due to dilation caused by the formation of new fractures prior to failure. This study is an engineering approach to identify the seismic velocity changes before and after each major seismic event in different time spans, with the ultimate goal of identifying a consistent pattern preceding major seismic events. Based on the case study analysis, the seismic velocity zones, demonstrate a meaningful correlation with the seismic velocity variations at hypocenters of the major seismic events in four out of the five events. The seismic velocity drop is more recognizable in shorter time spans. The average seismic velocity might increase after the event or stay at a new lower background level.

## 6.2 Introduction

Underground mining activities are periodical sources of induced seismicity to the surrounding rock mass. The rock mass tries to find a new equilibrium by deforming along existing structures or failing volumes of rock through rock bursts. These movements can be hazardous in the underground environment, potentially compromising the safety of the

miners and stability of the openings, both of which can have disastrous consequences. The unknown nature of rock mass creates a challenging working condition for mining operation. As the mining proceeds deeper, the potential stability hazards will be more severe. When the stress equilibrium in the rock mass changes due to the application of mining induced stress, the seismicity of the rock mass changes as well. (Szwedzicki 2003). Constant monitoring of displacement in open pit operations is done by slope stability radar, Lidar, InSAR, GPS and prisms to foresee slope failures and creeps at early stages of the failure. A similar tool which can detect changes inside the solid mass of rock can be helpful for underground deep mines. Microseismic monitoring systems have been used for this purpose in underground mines, tunneling and petroleum fracturing (Zhang et al. 2009; Rutledge, Phillips, and Schuessler 1998; Westman et al. 1994; Ma et al. 2018)

As the inside a human body can be monitored through CT scan, the inside of a rock body would be modeled with seismic tomography. Experimental lab tests show that the seismic velocity, which refers to the P-wave velocity in this study, is high in areas where the applied stress increases (Christensen 1965; Castagna, Batzle, and Eastwood 1985; Carlson and Miller 2004; Kern et al. 2001; Elbra et al. 2011; Nkosi et al. 2017). Therefore, the highly stressed areas can be recognized indirectly through the areas with high seismic wave velocity values. Moreover, the performance of the rock mass in highly stressed areas can be observed by continuous measuring of the seismic wave velocity variations.

The movements of bodies of rock, called "seismic events" can be minor with no harm to the mine openings or major, which might cause fatalities and extensive damage. Seismic events in underground mining can be very small with local magnitudes less than 0 or large with local magnitudes greater than 4. These large events can be felt on the surface for large distances away from the mine and can be very destructive to proximal excavations or infrastructure (Bethmann, Deichmann, and Mai 2011). The term rockburst was historically applied to all seismic events that were heard or felt by miners, but is now used to identify seismic events that cause observable damage or ejection of rock into openings. As seismic events larger than a magnitude 1.0 can release enough energy to result in a rockburst; this
paper refers to events with a local magnitude greater than 1.0 as "major events" to acknowledge their higher seismic hazard potential. The geometric location where the seismic event initiates is identified as the "hypocenter" of the event (Spence, Sipkin, and Choy 1989). In this paper, the approximate center of the highly-stressed area is called its "zone center" as described in chapter 4. The seismicity of the affected area is measured by a microseismic monitoring system, which included several receivers recording the body wave propagation emanating from seismic events.

In this study, the seismic data of five major events in a narrow-vein mine are analyzed by seismic tomography in order to investigate the changes in the seismic velocity of the abutment rock mass in different time spans. The seismic velocity variations are evaluated to determine how early a meaningful trend can be identified prior to the occurrence of an event, based on optimum node density and different lengths of time spans. The results of this study can be potentially used to identify highly stressed areas prior to the occurrence of a major event and hence precautions could be in place to secure or isolate the area. Moreover, it can be helpful in optimizing the mining practices and updating the stability designs as the mining proceeds due to actively checking the influence of the existing operations on the inferred stress state of the abutment rock mass.

## 6.3 Background

Rock mass failure can occur along the newly formed and merged fractures or existing fractures and planes of weakness (Goodman 1989; Brady and Brown 2006). These failures can cause rock bursts in brittle rocks under static or dynamic loading (Cook 1976). The brittle failure mechanism in this situation starts with closing fissures in the rock, followed by appearance of new microcracks, which are parallel to the applied stress. The axial stress-strain curve reaches to its yield point after extension of cracks intersect the edge of the specimen. The rock; however, may not collapse at this point as microcracks are merging continually until finally the fractured rock slides on the merged microcracks surface (Goodman 1989; Chen et al. 1998).

Failure along existing fractures is due to the shear stress and decrease in rock strength by the existing discontinuities (Sonmez, Ulusay, and Gokceoglu 1998; Goodman 1989; Lin and Librescu 1998; Hencher and Richards 2015). Usually, the shear face comprises various joints and the resistance to shear of the rock mass is due to the unbroken areas connecting the fissure called rock bridges (Wong and Chau 1998; Li, Chen, and Wang 2005; Ghazvinian, Nikudel, and Sarfarazi 2007). Chen et al. (2015) conducted laboratory tests on the rock bridge mechanism subjected to direct shear test by recording acoustic emission in rock mass and concluded that failure starts with accumulation of shear stress at the tip of rock bridges while it is equally dispersed on the shear surface. As shear stress increases, newer cracks plastically are formed and extended from the tip of the rock bridge until the rupture surface is coalesced. The failure along the rupture surface occurs when shear stress is equal to the shear strength, it is when the most acoustic events are recorded, followed by a rapid decrease in shear stress while cracks are propagating along the main fracture (G. Chen et al. 2015). These steps are demonstrated in Figure 6-1 along the variations of the deviatoric stress compared to the strain of the rock sample under compression (Goodman 1989).





To understand the rock failure analytically, different failure criteria have been developed to model the failure procedure corresponding to the applied stresses (Griffith A. 1924; Bieniawski 1974; Brady 1977; Hoek and Brown 1980; Amadei 1996). The Mohr-Coulomb criteria is the most applicable to predict rock failure under shear and normal stress considering friction angle along discontinuities and shear strength of the rock mass (Hoek and Brown 1980; Labuz and Zang 2012).

#### 6.3.1 Microseismic ground motion

The release of elastic energy as the result of ground movement generates seismic waves which propagate through the rock mass (Braile 2009). Brittle rock failure is the source of seismic waves including P-waves and S-waves defined as compressive wave and shear wave respectively (Buckingham 1998; Sheriff and Geldart 1995; Seya, Suzuki, and Fujiwara 1979). These sources of energy release, inducing seismic waves, are called seismic events (Blake and Hedley 2003).

Underground mining induces these ground movements which causes accumulative seismicity in the surrounding rock mass (Cook 1976; Erik C. Westman 2004; X. Ma et al. 2016). Brain et al. (2014) suggested that seismic waves from microseismic events can induce fractures in intact rock if the rock is highly stressed and strained over the critical levels (Brain et al. 2014). Acoustic monitoring of rock samples in these experiments shows that when microstructures are closing under pressure, seismic wave propagation velocity increases and attenuation decreases (Su et al. 1983; Sayers, Van Munster, and King 1990). Laboratory tests on rock samples and computational analysis shows the changes in stress distribution and ultrasonic wave velocity are correlated under compression (Scott et al. 1994; Thill 1972). He et al. (2018) and Scott et al. (1994) observed that body wave velocity increases parallel to loading by escalation of axial stress while it decreases perpendicular to the axial stress direction as shown in Figure 6-2 (Scott et al. 1994; T. M. He et al. 2018). Areas with higher velocity correspond to higher stress concentrations by consideration of void ratio (Werner et al. 1990). Additionally, high seismic velocity can also reflect higher rock stiffness (Toksöz, Cheng, and Timur 1976). Increasing depth below surface also increases seismic velocity by increasing the confining pressure due to overburden (Saxena, Krief, and Adam 2018; Wesseloo and Sweby 2008).



Figure 6-2. Average body wave velocity variations parallel and perpendicular to loading, modified after(He et al. 2018) and (Scott et al. 1994).

### 6.3.2 Seismic Tomography

Imaging the interior of objects by mathematically analyzing the body wave path through the object is called tomography (Radon 1917). Using seismic waves to image a rock mass is called seismic tomography (Braile 2009). A local seismic monitoring system (SMS) consists of several sensors, such as geophones, placed systematically around the area of interest and which are connected together as a time-synced array to record the oscillating ground movements associated with passing of the seismic body waves over time, commonly referred to as waveforms. The recorded waveforms can then be analyzed to locate the seismic event hypocenters and provide source parameters, such as when the event occurred  $(t_0)$ . Seismic body waves radiate away from the hypocenter as a spherical wave front, with the faster P-wave front going first, followed by the slower S-wave front. Seismic body waves can be reflected and refracted where they intercept significantly different rock mass properties, or around existing excavations. For relatively small volumes of rock, in this case areas within 5000 m<sup>3</sup> of the study area, the rock mass conditions are relatively constant so a uniform base velocity model can be assumed. The physical path of a seismic wave from the hypocenter to each sensor of the seismic monitoring system is a seismic ray. In a fairly uniform rock mass, the seismic rays are linear and the location of the sensors fixed, with the travel times of the P and S waves, denoted by  $T_P$  and  $T_S$  respectively (tp – t<sub>0</sub> =  $T_p$ , t<sub>p</sub> = arrival time of the P-wave), controlled by the P and S wave velocities and hypocenter location. t<sub>0</sub> is the origination of the event. The locations for this data set have a high confidence based on feedback from mine personnel. Seismic tomography uses seismic rays to estimate the changing seismic wave velocity through the rock mass. By combining all the seismic rays from multiple events locating in different locations within a rock mass and uniformly discretizing the volume into cubic nodes called voxels which can have the seismic velocity adjusted to fit the arrival times recorded, regions within the rock mass that have changing velocities caused by induced stress can be identified (Swanson, Boltz, and Chambers 2016; Luxbacher et al. 2008; Brzostowski and McMechan 1992; Dehn, Butler, and Weston 2018). In our study seismic velocity is referred to the P-wave velocity computed by seismic tomography.

The velocity of each voxel based on passive seismic tomography vary by changes in travel time of the recorded seismic events. Different geologies might show a different velocity compared to the background average velocity which is assumed to be constant based on the total number of events in the entire area of interest. However, the velocity changes in those areas are due to the induced stress regarding to mining.

The average seismic velocity of a rock mass before the influence of any ground motion is called the background velocity value. It is usually comparable to seismic wave velocities determined from core samples tested in a laboratory. Excavations cause increased induced stress on abutment rock masses, resulting in increased seismic velocity within those abutments (Young and Maxwell 1992). These areas are termed high-velocity zones in this study. Major seismic events potentially occur around high velocity zones. High and low velocity zones, which are correlated to the stress concentration level of the rock mass, are present in the vicinity of each other (Yang et al. 2015; Xu Ma et al. 2019a; Molka 2017).

### 6.4 Methodology

The seismic velocity variations are computed through several steps, starting from the recording of seismic data. The recorded data includes the sensor locations, the calculated locations of the seismic events, and the P-wave arrival time at each sensor. The seismic wave velocity is then calculated for each ray propagated from a single seismic event and received by each sensor based on the travel time and distance from source to receiver. The average background velocity for the area of study is calculated based on the linear regression of source-to-receiver travel distance over source-to-receiver time. The slope of this line is the average background velocity of a particular mining section.

Source parameters for events, such as energy, seismic moment, and magnitude, are calculated using the recorded waveform data by the SMS on site. The seismic data may be analyzed over different time spans such as monthly or even daily depending on data density and ability to resolve changes in parameters without losing reliability (Dehn, Butler, and Weston 2018). In order to evaluate the changes before and after each major seismic event, the middle time spans (including  $t_0$  as the origin) are set at the occurrence date of the major seismic events. Previous and post time spans are defined counting back or forth from the origin time. The input of the tomographic analysis is created based on event's and sensors' coordinates and travel times of the received rays in the desired time spans included. Moreover, the extent of the input should be consistent. For example, if the major event occurs on the 6<sup>th</sup> of May, the middle time span including t<sub>0</sub> for weekly analysis is from May 6<sup>th</sup> to May 12<sup>th</sup>. The previous and post time spans can be defined based on this origin time.

Prior to computing the tomograms, the size of voxels should be determined large enough to include sufficient number of rays for a reliable tomographic analysis. In this study two different voxel sizes are considered. The input files are analyzed considering the defined voxel dimensions based on Simultaneous Iterative Reconstruction Technique (SIRT) tomography algorithm in different continuous iterations as explained by Ghaychi Afrouz and Westman (2018) (Ghaychi Afrouz and Westman 2018). The number of iterations should be enough to confidently determine the inflection point, as the elbow of the graph, along a plot of root mean square of the difference between measured and calculated travel times. The optimum iteration number based on the inflection point should be consistent for all of the time spans.

After running all the tomograms for each time span, the results can be visualized by interpolating the calculated velocities for each timespan. The major events can be located as hypocenters in 3D visualization and high velocity zones associated with each event can be determined. The high velocity zones are recognizable in all of the time spans prior to the event occurrence. The approximate geometric center of each high velocity zone is labeled as the zone-center. The time span with the highest average velocity value is the best to determine the zone-centers. After locating hypocenters and zone-center can be computed and graphed in different continuous time spans. Figure 6-3 demonstrates the flow chart of this procedure from recording seismic data to graphing the variations of the seismic velocity around hypocenters and zone centers.



Figure 6-3. Seismic velocity variation graph flowchart.

#### 6.4.1 Seismic Data in a narrow vein mine

The seismic data from two different mining sections of a deep narrow-vein mine were analyzed. The mine is located in the western U.S.A, along a silver-rich belt veins with lead and copper byproducts. The active mining sections studied in this research are along this belt with dominant faults striking WNW (Mauk and White 2004). The data were recorded by 50 seismic sensors installed throughout the underground workings. The excavations associated with the two sections are shown in Figure 6-4, which includes location of all of the seismic sensors, the mine coordinates, and boundary of the velocity model which encompasses all voxels. As this is a narrow-vein mine with strong structural controls on the mineralization, the majority of the excavations closely follow the veins creating steeply dipping planes of continuous excavations and remnant pillars. Only excavations associated with the study areas are included in the figures for simplicity. The microseismic system is connected to ESG HHS software and the released energy and magnitudes are calculated by the program.



Figure 6-4. Section views of the two study areas (grey lines), including sensor locations (red squares), and mine grid coordinates. The vertical axis is elevation as mean sea level. All measurements are in meters. The blue outline denotes the edge of the velocity model. Only excavations associated with the study are included for simplicity.

The background velocity of these two sections are 5741 m/s and 5757 m/s respectively for sections 1 and 2 as shown in Figure 6-5 Mining Section 1 had active production and development activity during the year of recording. Mining Section 2 was inactive during

the study period and had been inactive for a few years prior to the study. Both sections had older mining excavations that had been backfilled many years previously.



Figure 6-5. Travel distance versus travel time for all seismic rays recorded in each section, with data from in Section 1 in the left graph, and data from Section 2 in the right graph. Linear regression of the data points provides the average velocity in each section.

## 6.5 Results

Based on the released energy, number of seismic events, and their magnitudes, three major seismic events were identified as occurring in Section 1, and two major seismic events identified as occurring in Section 2. Figure 6-6 demonstrates the cumulative energy and number of seismic events in both sections.

Figure 6-7 shows the same energy profiles from Figure 6-6 but is now compared to the Moment Magnitude ( $M_W$ ) for each event recorded on the secondary y-axis. The average  $M_w$  in the Section 2 is higher than for Section 1, which is expected as Section 2 is approximately 300 m deeper than Section 1. The major seismic events are not only recognized based on  $M_w$ , but also on their significantly larger shear energy release.



Figure 6-6. Cumulative energy and number of events in each mining section. The vertical light blue lines indicate when each major event occurred, cumulative Energy released by all seismic events is the dark blue line, and the dashed orange line shows the cumulative number of total events.



Figure 6-7. Cumulative energy compared with individual event moment magnitudes of events in both sections. The vertical light blue lines indicate when each major event occurred, cumulative Energy released by seismic events is the dark blue line, and vertical orange lines indicate Mw for each event in the time series.

Two different time spans for data analysis were selected; weekly (7-days) and 3-days. Different time windows were tested to determine which timespan showed the most divergence from the background velocity. Long timespans of 30 and 14 days were

smoothing out the data too much for meaningful comparison. The 7-days time span was the most appropriate to identify the high velocity zones. In order to analyze the daily changes, 24-hours time span did not contain enough numbers of rays in each voxel, therefore a 72-hour time span was selected. There are 48 hours of overlap between each two continuous 72-hours timespans.

The tomogram results represent the average velocity value of each voxel during the time span being analyzed. For example, the tomogram of a week prior to an event represents the average velocity from 7 days before the event to a day before the event and the next tomogram, which includes the major event, starts from the day of the event to 7 days later. The exact time of occurrence of the major events are not considered and each day starts from 12:00 AM midnight local time.

The higher iteration number was tried first to assure the root mean square of the difference between measured and calculated travel time reaches an inflection point around a certain iteration number which is persistent for all weeks. For both mining sections, the tenth iteration shows the elbow which is the best result to visualize data, similar to what was observed in chapter 3 at Figure 6-. Optimum iteration number based on the elbow method of the root mean square of the residual of the ray path travel times in each iteration. The10<sup>th</sup> iteration shows the inflection point as the optimum number of iterations for this area.



Figure 6-8. Optimum iteration number based on the elbow method of the root mean square of the residual of the ray path travel times in each iteration. The10th iteration shows the inflection point as the optimum number.

Voxel size should be large enough to include sufficient rays to compute the velocity with high confidence and minimal variation caused by individual events, but not so large that trends in the velocity are lost in the noise caused by too many events. The values of 29 m and 56 m are selected for voxels spacing based on dividing the smallest axis of the entire volume into at least 40 voxels and 20 voxels correspondingly. The maximum number of voxels based on the minimum number of raypaths passing through the area is 40. Therefore, 29 m is the minimum voxel size in this area. In 29 m in areas with less ray density the velocity calculations might not be very accurate especially in smaller time spans. As 29 m voxels are relatively small compared to the entire volume, the tomograms might be affected by abrupt changes and environmental noises hence larger voxel size of 56 meters are calculated as well. The tomograms of 56 meter voxels during a week illustrates larger high velocity zones which smoothes out the data. Therefore 29 m voxel

size are chosen for further analysis. The results of analysis with 56 m voxels are shown in the appendix.

Based on the tomograms for Section 1, three high velocity zones were recognized. Each associated with at least one major seismic event. The approximate centers of these zones are identified as Zone center A, Zone center B and Zone center C respectively as shown in Figure 6-9. Section 2 also had three high velocity zones are recognized, for which there were two associated major events as is shown in Figure 6-10. For labeling the hypocenters or zone centers first the section number is stated and then the letter or number of the zone center or the hypocenter.







Figure 6-10. Cross section (left) and long section (right) views of Section 2 showing the locations of the two major events, and the locations of the three high velocity zone centers.

As stated earlier, long time spans can smooth out the velocity transitions, so to gain a more detailed understanding of the magnitude of the velocity variations prior and post each major seismic event, shorter time spans were considered. Ideally, the analyses would be done on a daily bases using 24-hours of data to more closely track stress changes caused by daily mining activities which is more useful for short term hazard management. However, there are not sufficient number of rays passing through each voxel to have reliable tomograms at this time scale resolution. Enlarging the voxel size to capture sufficient rays is possible, but also results in smoothing of data and less data points within the volume of interest. For this paper all results were done using the smaller 29 m voxel size. The results using the 56 m voxel size are included in the Appendices. Therefore, a 3-day (72-hour) time span was used which provides 48-hours of overlap with the preceding time span providing enough seismic rays for reliable tomograms and minimizing the highly erratic trends that result from too few data points. The weekly and 3-day changes in seismic velocities in the zones and around the hypocenters for Section 1 were analyzed in chapter 4. Figures 6-11 and 6-12 show the weekly seismic velocity variations from Section 2 for events 1 and 2. Figures 6-13 and 6-14 show the 3-day seismic velocity variations for the same data. The hypocenters of these events are labeled as 1 and 2. The three high velocity zone-centers are labeled in the figures as A, B and C.



Figure 6-11. weekly seismic velocity tomograms of Event 1 in Mining Section 2 for a month before and after the event. Hypocenter 1 is marked with and astrix (\*) in the first tomogram and the zone center A is marked with (+). The section plane is approximately perpendicular to the vein.



Figure 6-12. weekly seismic velocity tomograms of Event 2 in Mining Section 2 for a month before and after the event. Hypocenter 2 is marked with (\*) in the first tomogram and the zone center B is marked with (°). The section plane is approximately perpendicular to the vein.

The 3-day time span is more sensitive to a smaller o the voxel size due to the fewer number of the rays accumulated in the average. Therefore, the 3-day tomograms with different voxel sizes of 29 meters and 56 meters are compared for all events as they are demonstrated in figures 6-12 and 6-13 for Section 2.



Figure 6-13. Every 3-day seismic velocity tomograms of Event 1 in Mining Section 2 for a week before and after the event. Hypocenter 1 is marked with (\*) in the first tomogram and the zone center A is marked with (+). The section plane is approximately perpendicular to the vein.



Figure 6-14. Every 3-day seismic velocity tomograms of Event 2 in Mining Section 2 for a week before and after the event. Hypocenter 2 is marked with (\*) in the first tomogram and the zone center B is marked with (°). The section plane is approximately perpendicular to the vein.

The variations of the seismic velocity in these zones are calculated according to SIRT tomography algorithm considering the curved raypath passing through the rock mass and

averaging the velocity amounts of the voxels in the target area. The variations of the seismic wave velocity in high-velocity zones are compared with the closest hypocenter to their zone center. Looking all events closer to the occurrence of the major event a closer investigation in 14 days prior to the events shows that there is a drop in velocity within 4 days of the event. As each tomogram includes 72 hours (3 day) of raypaths, each 4 day period is actually a week prior to the event occurrence. The velocity amounts for both mining sections in 50-meter spheres around the hypocenters, and 100 m spheres around zone-centers are averaged based on each tomogram.

#### 6.5.1.1 Certainty of Computations

The confidence interval of computational tomography is calculated by bootstrap method (Sacchi 1998). The inaccuracy of the results is calculated by resampling raypaths. In this method the input data is randomly sampled, the tomographic calculation is applied on the new sample, the sampled data are replaced in the population and sampled again for another round of analysis (Efron 1979). There is a seismic velocity calculation for each round resulting in an average velocity for any chosen time span. The goal is to determine how much the average velocity of the samples at a certain time deviates from the true value calculated using the entire population.

In this study, every tenth ray path starting from 1st, 2nd, 3rd and 4th rows have been removed from our population to create different samples 10% smaller than the entire area by the number of the received ray paths. The average velocity is calculated in both situations and compared to the true population of data. The maximum, minimum, and average of the sampled analysis are shown on the velocity variation graphs as the inaccuracy interval of two random points. The average confidence of interval based on bootstrapping in this study is about 44 m/s which is about 0.5 percent of the measured seismic velocity of the selected timespan. The average location error for all of the seismic events is 31 m.

Using confidence intervals, a more detailed analysis focusing on the rock closer to the event hypocenters and within the high velocity zones was done to evaluate the gross trend of velocity decrease in the week(s) preceding an event shown in Figures 6-15 and 16 above. Figures 6-17 and 6-19 demonstrate the weekly changes in the average seismic velocity in 50 m radii from the hypocenters of events in mining section 1 and mining section 2 respectively. The target time frame based on the 500-m radius analysis done previously is highlighted in blue and is the week or weeks (week -1 or -2, respectively), prior to week zero which includes the event. The uncertainty of the calculation is shown as range of deviation for these weeks.

As the high velocity zones are larger than 50 meter in some cases, the changes in seismic velocity are also computed using a 100 m radius from zone centers, which are shown in Figures 6-18 and 6-22. Accordingly, Figures 6-17 and 6-19, 6-21 and 6-23 show the 3-day variations of average velocity around hypocenter and zone centers for all 5 events. The changes within 4 days to the event are highlighted and the uncertainties are shown in ranges for random pints. The 4-days period is actually a week of received data.



Figure 6-15. Weekly changes of seismic velocity in Mining Section 1 around hypocenters. The highlighted area shows the expected decrease within two weeks of the event occurrence. The upward arrow, downward arrow and the red dot in the middle respectively show the maximum, minimum, and, average error.



Figure 6-16. Daily changes of seismic velocity in Mining Section 1 around hypocenters calculated based on overlapping every 3-day calculation. The highlighted area shows the expected decrease within two weeks of the event occurrence. The upward arrow, downward arrow, and red dot between them respectively show the maximum, minimum, and average error.



Figure 6-17. Weekly changes of seismic velocity in Mining Section 1 around zone centers. The highlighted area shows the expected decrease within 2 weeks of the event occurrence. The upward arrow, downward arrow and the red dot between them respectively show the maximum, minimum, and average error.



Figure 6-18. Daily changes of seismic velocity in Mining Section 1 around zone centers calculated based on overlapping every 3-day calculation. The highlighted area shows the expected decrease within 2 weeks of the event occurrence. The upward arrow, downward arrow and the red dot between them respectively show the maximum, minimum, and average error.



Figure 6-19. Weekly changes of seismic velocity in Mining Section 2 around hypocenters. The highlighted area shows the expected decrease within 2 weeks of the event occurrence. The upward arrow, downward arrow and the red dot between them respectively show the maximum, minimum, and average error.



Figure 6-20. Daily changes of seismic velocity in Mining Section 2 around hypocenter, calculated based on overlapping every 3-day calculation. The highlighted area shows the expected decrease within 2 weeks of the event occurrence. The upward arrow, downward arrow and the red dot between them respectively show the maximum, minimum, and average error.



Figure 6-21. Weekly changes of seismic velocity in *M*ining Section 2 around zone centers. The highlighted area shows the expected decrease within 2 weeks of the event occurrence. The upward arrow, downward arrow and the red dot between them respectively show the maximum, minimum, and average error.



Figure 6-22. Daily changes of seismic velocity in Mining Section 2 around zone centers calculated based on overlapping every 3-day calculation. The highlighted area shows the expected decrease within 2 weeks of the event occurrence. The upward arrow, downward arrow and the red dot between them respectively show the maximum, minimum, and average error.

The quantitative changes in the value during the highlighted zone of each graph is calculated and summarized in Table 6-1 to investigate the events with decrease or increase in expected time period. In Table 6-1 the arrows determine the drop or raise within the specified time intervals for each event.

Table 6-1. Quantitative seismic velocity drops or raises around hypocenters and zone centers within 2 weeks prior to the event and within 4 days prior to the event. The events are labeled based on the mining section and the event number respectively. For example, Event 1-2 refers to the Event 2 in Mining Section 1.

Velocity Change (m/s)				
	Hypocenter		Zone Center	
	2 weeks prior	4 days prior	2 weeks prior	4 days prior
event 1-1	个 18	个 16	↓ -162.3	↓ -70.6
event 1-2	↓ -130	↓ -18	↓ -71.0	↓ -119.4
event 1-3	↓ -63	↓ -105	个 15.8	↓ -107.6
event 2-1	个 30.0	个 35.2	↓ -4.2	<b>↑</b> 15.4
event 2-2	↓ -81.6	↓ -0.6	↓ -179.5	↓ -15.0

### 6.6 Discussion and Observations

Generally, it is observed that a major seismic event occurs when the average background velocity level decreases and the total number of raypaths are increased. Therefore, the total number of raypaths and the average velocity of the entire area can be our first lead in detecting major seismic events. Moreover, the hypocenters of the major seismic events are located at the edge of the clearly recognizable high-velocity zones in cross sectional tomograms.

The seismic velocity changes in high-velocity zones are correlated to the changes of the seismic velocity at hypocenters. According to the Table 6-1, four out of five of the events show drop in their velocity within 4 days of the event occurrence in both zone centers and hypocenters. This correlation is observed in three out of five events for weekly analysis within 2 weeks of the events' occurrence.

According to weekly analysis with both voxel sizes, all major events occurred during or at the end of a decreasing trend, which had begun at least a week prior to the event. This trend was shown using both voxel data within 50 meters' radii distance from the hypocenters, and also the average velocity of the entire section within 500 meters' radii. In four out of five major events, the seismic velocity intensity reduces in vicinity of the hypocenter of the event based on week by week analysis. However, in Event 1 in the second mining section it decreases more dramatic significantly compared to the previous weeks.

Based on the every 3-day analysis of all five events, the seismic velocity decreases in highvelocity zones within 4 days of all five events. The high-velocity zone might go back to the background velocity level, such as after events 1 and 2 in mining section 2, or find a new background velocity which can be lower than the original background level. This destressing condition is observed post event 1 in mining section 2 where mining operations had a low to moderate advance rate. After event 2 and 3 in mining section 1, however, the background seismic velocity level increases as the mining advance rate is high. The geological conditions and existing fractures and faults might influence the mechanism of the major event which could affect the velocity variations. Mining sequences, drilling, and blasting can also affect the seismic velocity in the abutment rock mass, especially in the 3-days analysis which is more sensitive to abrupt changes compare to weekly analysis which averages more raypaths in a longer period of time.

The typical trend of the velocity changes and the background velocity levels are tied to the rock type and fracture density; therefore, different geologies can have different trends even in the same mining area. The typical or signature seismic velocity trend of each zone for every section can be identified by continuous monitoring of the seismic velocity variations.

### 6.7 Conclusion

As it is discussed above, all of the five seismic events occurred during or immediately following notable trends of decreasing average velocity for high velocity zones that were proximal to the eventual location of the event hypocenter. All five seismic events in the two mining sections studied occurred during or after a decrease-increase pattern at the eventual hypocenters locations. The decrease-increase pattern comprises a decrease in seismic velocity prior the occurrence of the event followed by an increase immediately prior to the event or including it.

The average seismic velocity of the high velocity zones within 100 meters of the zonecenters followed the same pattern as the hypocenters. Thus it can be concluded that high velocity zones are influenced by the velocity changes around the hypocenter preceding the upcoming seismic event, and these changes can be detected by continual monitoring the seismic velocity variations in the high velocity zones, which are easily identifiable preevent whereas the final event location cannot be precisely predicted.

The average velocity of the entire rock mass reduced prior and during the seismic events likely as a result of existing crack extension and dilation in rock mass. The high velocity zones detected by tomography are identified by having seismic velocities higher than background seismic velocities due to the induced stress accumulation. The value of seismic velocity in these areas; however, decreases prior to occurrence of the seismic events. These changes are not always large enough to drop the average velocities within the zones back down to the average background level.

Seismic tomography has the potential to monitor the performance of the rock mass as a continuous volume vs. by point data collected using traditional geotechnical instrumentation or mapping. This back analysis study demonstrated the high velocity zone a pattern reduction of seismic velocity of the hypocenter a week to 3-days prior to the occurrence of the seismic events. Successful application of the method could provide a more confident estimate of increasing seismic hazard prior to event occurrence allowing operations to take precautions to change the mining advance rate as the source of induced stress which impact the high velocity zone. The reduction pattern in the seismic velocity trend of the hypocenter and accordingly the high velocity zones is likely affected by rock type and existing structures in the rock mass and can be recognized for each specific area, site by site due to consistent seismic monitoring.

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# Appendices

This appendix includes the tomograms and velocity graphs with 56 m voxels for both mining sections 1 and 2.



Figure 6-23. Every 3-day seismic velocity tomograms of event 1 in Mining Section 2 for a week before and after the event with 56 m voxel size. Hypocenter of the event and the potential zone centers are demonstrated with red dots. The section plane is approximately perpendicular to the vein.



Figure 6-24. The weekly and every 3-day velocity graphs of the entire area of 500 m around the hypocenters of the 3 events in mining section 1 with 56 m voxel size.



Figure 6-25. Weekly changes of seismic velocity in mining section 1 around hypocenters with 56 meters' voxel size. The highlighted area shows the expected decrease within 2 weeks of the event occurrence. The upward arrow, downward arrow and the red dot in the middle respectively show the maximum minimum and the average error.


Figure 6-26. Daily changes of seismic velocity in mining section 1 around hypocenters calculated based on overlapping every 3-day calculation with 56 meters' voxel size. The highlighted area shows the expected decrease within 2 weeks of the event occurrence. The upward arrow, downward arrow and the red dot in the middle respectively show the maximum minimum and the average error.



Figure 6-27. Weekly changes of seismic velocity in mining section 1 around zone centers with 56 meters' voxel size. The highlighted area shows the expected decrease within 2 weeks of the event occurrence. The upward arrow, downward arrow and the red dot in the middle respectively show the maximum minimum and the average error.



Figure 6-28. Daily changes of seismic velocity in mining section 1 around zone centers calculated based on overlapping every 3-day calculation with 56 meters' voxel size. The highlighted area shows the expected decrease within 2 weeks of the event occurrence. The upward arrow, downward arrow and the red dot in the middle respectively show the maximum minimum and the average error.



Figure 6-29. Every 3-day seismic velocity tomograms of event 2 in mining section 2 for a week before and after the event with 56 m voxel size. Hypocenter of the event and the potential zone centers are demonstrated with red dots. The section plane is approximately perpendicular to the vein.



Figure 6-30. The weekly and every 3-day velocity graphs of the entire area of 500 m around the hypocenters of the 2 events in mining section 2 with 56 m voxel size.



Figure 6-31. Weekly changes of seismic velocity in mining section 2 around hypocenters with 56 meters' voxel size. The highlighted area shows the expected decrease within 2 weeks of the event occurrence. The upward arrow, downward arrow and the red dot in the middle respectively show the maximum minimum and the average error.



Figure 6-32. Daily changes of seismic velocity in mining section 2 around hypocenters calculated based on overlapping every 3-day calculation with 56 m' voxel size. The highlighted area shows the expected decrease within 2 weeks of the event occurrence. The upward arrow, downward arrow and the red dot in the middle respectively show the maximum minimum and the average error.



Figure 6-33. Weekly changes of seismic velocity in mining section 2 around zone centers with 56 meters' voxel size. The highlighted area shows the expected decrease within 2 weeks of the event occurrence. The upward arrow, downward arrow and the red dot in the middle respectively show the maximum minimum and the average error.



Figure 6-34. Daily changes of seismic velocity in mining section 1 around zone centers calculated based on overlapping every 3-day calculation with 56 meters' voxel size. The highlighted area shows the expected decrease within 2 weeks of the event occurrence. The upward arrow, downward arrow and the red dot in the middle respectively show the maximum minimum and the average error.

# Chapter 7 - A conceptual protocol for integrating multiple parameters for risk assessment due to induced seismicity in a deep mine

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## 7.1 Abstract

Typically, the time-dependent b-value has been shown to decrease prior to the occurrence of a higher-magnitude event, thus providing a possible indicator of the timing of a significant event. The Energy Index relates seismic energy to seismic moment and an increase in the Energy Index has been associated with an increase in rock mass stress levels. The distribution of P-wave velocity also indicates rock mass stress levels and is provided from time-lapse passive seismic tomography. Finally, prior studies have correlated an increased production rate (blast rate) to higher stress concentrations, potentially triggering a seismic event. Therefore, Energy Index, P-wave velocity, and blast rate may be correlated to stress levels within the rock mass and may imply the magnitude and timing of an event. In this case study, these parameters are used in a back analysis to define a safety protocol for a deep, narrow-vein, underground mine. A catalog of b-value, Energy Index, P-wave velocity, and mine excavation blasting rate, was developed and integrated as a concept of hazardous thresholds. The combination of these various parameters can be helpful in determining the potential for high-risk times and locations due to induced stress.

# 7.2 Introduction

Unexpected seismicity in deep underground mines can result in unsafe working conditions and can negatively impact production at a mine. For this reason, microseismic monitoring has been used for more than half a century to monitor induced seismicity related to stress redistribution associated with mining excavation (Mendecki, 1996). Many hundreds of microseismic events can be recorded and analyzed with high precision of measurements of location and time of the event occurrence (Urbancic and Trifu, 2000). The modern realtime seismic monitoring is used in mines to monitor the changes in microseismicity in order to predict potential instabilities (Mendecki, 1996). Seismic parameters such as bvalue, Energy Index and seismic velocity calculated from real-time seismic monitoring can be helpful in understanding the rock mass behavior in order to define meaningful trends leading to the occurrence of a major shock (Swanson et al., 2016).

The risk assessment in underground mines is calculated in quantitative, qualitative or hybrid based on the likelihood of the potential hazards and their negative impact weight (Kenzap and Kazakidis, 2013; Dominguez, 2019). The quantitative methods estimate the influence of each factor on cash flow. The most common methods for these numeric calculations are three-point estimation, discrete probability and stochastic modeling (Mackenzie, 1969). Qualitative methods, however, evaluate the severity of each factor based on predefined categories. The ground control risk in hard rock mines was developed as roof-fall-risk index (RFRI) method. This method includes geological and discontinuities factors, potential failure mechanism, roof profile and moisture content (Iannacchione et al., 2007). A microseismic monitoring system can adjust this technique based on the number of recorded events compared to background seismicity rate. According to this adjustment if there is no detectable cluster of seismic events, the chance of producing new fractures is low and the RFRI index reduces (Iannacchione et al., 2007).

In seismic hazard identification, the b-value based on Gutenberg-Richter is the most common method. The Gutenberg-Richter Law relates the number of seismic events in a location to the magnitude of the events. Typically, there are ten times as many events of a given magnitude as there are for a magnitude that is one higher (Gutenberg and Richter, 1944). The slope of a linear regression of the frequency to the magnitude of the events is defined as seismic b-value (Gutenberg and Richter, 1954). Field studies and laboratory experiments show that b-value and applied stress are correlated and abnormalities in b-value indicate changes in applied stress (Lockner, 1993; Okal and Romanowicz, 1994;

Ashtari Jafari, 2008; Rivière et al., 2018). Generally, it was observed that major seismic events occurred at the relative peak of the b-value, mostly after a decrease just prior to the increasing trend (McGarr, 1971; Vallejos and McKinnon, 2011; Ma et al., 2018). There are however, uncertainties in estimating the occurrence of major seismic events using b-value due to different magnitude binning methods, variation in failure mechanisms, induced stress redistribution and microseismic system ray path coverage (Marzocchi and Sandri, 2003; Leptokaropoulos and Adamaki, 2018).

Another method, Energy Index (EI), is a substitute method to assess the performance of a rock mass subjected to induced stress based on the released energy amount compared to the average energy for a particular moment (Aswegen and Butler, 1993). The average EI evaluation during a particular time and volume is modified as the Average Scaled Energy Scale (ASEI) (Dehn et al, 2018). Field studies show that EI increases by the accumulation of induced stress while the released energy decreases when cracks are formed and merged in the rock. Therefore, the occurrence of major seismic events is expected after a reduction in EI (Minney et al., 1997; Lynch and Mendecki, 2001; Dehn et al, 2018).

P-wave velocity is the other seismic parameter that is correlated to induced stress and can be mapped by passive seismic tomography (Westman, 2004). The tests on the rock samples show velocity changes by increasing the applied stress at low-stress zones. When stress amount reaches its peak a slight to moderate decrease might be seen in the velocity based on the orientation of the sensors to the loading direction (Scott et al., 1994; He et al., 2018). The field data shows that high-velocity zones correlate with highly stressed areas (Zimmerman and King, 1985; Westman et al., 2001). Numerical analysis matches with field observations as well (Ghaychi Afrouz and Westman, 2018). Based on the P-wave arrival time to sensors, a velocity model is made in order to compute seismic velocity for each voxel in surrounding rock. A tomogram is a two-dimensional cutting section of the computed velocity distribution, then the variations of the average velocity can be estimated in the volume of interest. Moreover, the blasting rate has a direct impact on induced seismicity (Mendecki, 1996). Seismic tomography and the EI method are used to monitor the impact of the blasting.

Real-time seismic monitoring includes recording seismicity and computing seismic parameters in desired time-lapses. In addition, after initial records and calibrating the system, some critical thresholds for different seismic parameters can be determined considering the characteristics of the area, such as geology. These thresholds are based on the concept of the alarm thresholds for displacement rate in open pit slopes stability monitoring.

Different monitoring tools, such as terrestrial radars, InSAR, GPS, robotic total stations and etc., with various accuracy and range, are used in open pit mines to determine landslide or rapid slope movement in early stages of failure (Kumar and Villuri, 2015). Slope Stability Radars (SSR) are the most common tools with assigned critical thresholds based on the geology, orientation of the structures regarding the geometry of highwall and moisture level. Operation crews and dispatchers have clear protocols of action in answer to each of these thresholds when different alarms go off (Saunders et al., 2016; Kumar and Rathee, 2017). The most critical alarm levels usually recommend site evacuation, which should be approved by the geotechnical experts to ensure it is not due to noise or atmospheric errors. The geotechnical crew will check these thresholds periodically for required modifications as mining progress.

This paper draws from surface mine slope stability monitoring protocols to develop and present a case study for assessing induced seismicity associated with major seismic events in a deep hard rock mine. A back analysis approach is applied to seismic data in different steps and critical levels prior to the occurrence of each event are explained in order to determine the precursory conditions. These parameters can be used in risk analysis of probability of failure with the defined limits identified in this study.

#### 7.3 Data and Methods

Data of seismic records of a deep hard rock mine during a year is analyzed for this study. The mine is located at an ore producing belt with generally steep faults striking WNW. The mineralization of the area is along narrow steep veins with about 1 to 3 m widths. The principal stress is in the direction of the major faults with relatively high horizontal stress. The mining method is cut and fill (Mauk and White, 2004; Dehn et al, 2018).

The mine includes 2 active mining sections covered with 50 sensors as shown in Figure 7. Three major seismic events in Mining Section 1 and two major seismic events in Mining Section 2 with a moment magnitude of more than 2.0 were recognized. The blue point in Figure 7-1 shows the hypocenters of these events.



Figure 7-1. Mine openings in two active sections are shown in gray. The red squares show the sensors' distribution and the blue squares show the hypocenters of the five events.

More than 12000 seismic events were recorded in each of these mining sections. The moment magnitude of these events and the cumulative energy of these events are calculated with ESG's Windows-based Hyperion Seismic Software (HSS) Suite as shown in Figure 7-2. The major jumps in the figure indicate the occurrence of the major events. The moment magnitudes of the events vary between -3 to 1.8 in both mining sections as shown in table 7-1.



Figure 7-2 .The seismicity in the form of the cumulative number of events is shown in red and the cumulative released energy is shown in blue for both mining sections.

Major Seismic Event		Day	time	Moment Magnitude
Mining Section 1	1	65	4:43:51 AM	1.62
	2	199	7:46:01 AM	1.81
	3	216	3:19:45 PM	1.75
Mining Section 2	1	33	7:54:55 PM	1.48
	2	248	6:46:41 PM	1.76

Table 7-1. Times, locations, and magnitude of major seismic events at two mining sections

#### 7.3.1 B-Value calculations

According to Guttenberg-Richter law, for the total number of events greater than or equal to the minimum magnitude of completeness (N(m)), the power of seismicity (b-value) is defined as Eq. (7-1), where a-value is constant.

$$\log(N(m)) = a - bm \tag{7-1}$$

The most accurate b-value is calculated by maximum likelihood of the logarithm of the data which requires a minimum of 2000 events to optimize results and minimize inaccuracy (Aki, 1965). The timespans are developed based on every 2000 seismic events with 200

events shifting frame, hence every continuous two spans have 1800 overlapping events. As the spans are based on the number of events, the timing range of each span might vary from a day to more than a month.

The b-value of each span is calculated based on maximum likelihood of logarithmic distribution of the cumulative magnitude frequencies as shown in Figures 7-3 and 7-4. The point of maximum curvature of the logarithmic plot is called magnitude of completeness (Mc) and is calculated based on the goodness of fit method as explained by Ma et al, 2018. The goodness of fit (R) is function of recorded and synthetic cumulative number of events (Bi and Si respectively) as defined in Eq. (7-2) for a range of magnitude (i) with bin width of 0.1.



Figure 7-3. Cumulative numbers of seismic events as functions of magnitude for the second span including Event 1 at Mining Section 1.



Figure 7-4 Cumulative numbers of seismic events as functions of magnitude for the first span including Event 1 at Mining Section 2.

#### 7.3.2 Energy Index (EI)

The released energy from seismic events with different magnitudes can be evaluated with Energy Index method. For this purpose, first, the logarithmic graph of energy to seismic magnitude should be graphed as shown in Figure 7-4. Then the average expected energy for each event within the range of moment magnitudes can be estimated ( $E(m_{ave})$ ). Finally, EI during a specified timespan can be calculated with normalizing the realized seismic energy of each event (E(m)) to the average expected released energy of an event with an identical magnitude as shown in Eq. (7-3).

$$EI = \frac{E(m)}{E(m_{ave})}$$
(7-3)

The seismic data might not be within our area of interest or related to the induced seismic event. Therefore, the irrelevant data can be eliminated in 7-the logarithmic plot of energy-magnitude before calculating the E(mave). Figures 7-5 and 6 respectively show the cut-off levels for the second span including Event 1 in Mining Section 1 and the first span

including Event 1 in Mining Section 2. Dehn et al., 2018, introduced Scaled Energy Index (SEI) in order to highlight the spans with EI above or below a based line of the average energy index, shown in Eq. (7-4).

$$SEI = \begin{cases} EI - 1 & EI > 1 \\ -(1/EI) + 1 & EI < 1 \end{cases}$$
(7-4)

For consistency in analysis, SEI is calculated for events within the moving timeframes similar to the b-value calculations. The SEI values are averaged over the spans and the Average Scaled Energy Index (ASEI) variations during a year of study is calculated for each span.



Figure 7-5. The cut-off limits of the logarithm of released energy to the logarithm of its magnitude for the second time span in Mining Section 1 including its Event 1.



Figure 7-6. The cut-off limits of the logarithm of released energy to the logarithm of its magnitude for the first time span in Mining Section 2 including its Event 1.

#### 7.3.3 Average Velocity and Seismic tomography

The velocity of each ray path propagated from seismic events is calculated based on the Pwave travel time and distance from the sensor, with known coordinates, to the event, with unknown coordinated. The P-wave arrival times and the calibrated velocity model, for locating the seismic events, are computed by ESG solution software.

The background velocity level is based on the slope of the linear fit to the travel time - distance plot of the recorded events. Figure 7-7 shows the background velocity of about 5740 m/s for both mining sections in the case study.



Figure 7-7. Scatter plot of distance vs travel time from seismic source locations to sensors. The slope of the graph shows the background velocity level of the area.

Considering the constant timeframes with 2000 events, the average velocity of all ray paths associated with these events is calculated for a bulk estimation of the average seismic velocity variations in the entire area during the year of study. When stress is concentrating, b-value and EI increase to their maximum and the average velocity increases.

After having the lead about the proximity of the location and the time of the highly stressed zones, the seismic velocities can be calculated in the smaller volume of interest with shorter

time intervals using seismic topography. For this purpose, the entire area is divided into smaller voxels through which at least hundreds of ray paths are recorded. Then based on the Simultaneous Iterative Reconstruction Technique (SIRT) algorithm, with curved rays tracing, the seismic velocity of each voxel during the desired timeframe is computed (Jackson and Tweeton, 1947; Westman et al., 1994).

#### 7.3.4 Mining Advance rate

Blasting is considered as the most significant mining-induced disturbance subjected to the underground rock mass. Blast-related failures are mostly in less stressed rocks with reduced stored strain energy such as fractured rock mass (He et al., 2018). Monitoring the mining advance rate due to blasting is critical to recognize the most vulnerable areas to blasting tremors.

In this study, only the blast rates and mining advance rates in Mining Section 1 are evaluated as the blasting data of Mining Section 2 were not provided by mine site. The mining advance rate per day is calculated based on the ratio of the distance between locations of the two consecutive blasts to the number of days they are apart. Figure 7-8 demonstrates the variations of the mining advance per week at the days of blasting in Mining Section 1. The numbers of blasts per day for events 1, 2 and 3 are 1, 0 and 2 respectively.



Figure 7-8 Mining advance rate (m/day) at blast days. The days of the occurrence of events are labeled in red. There is no blast on the day of the occurrence of Event 2.

### 7.4 Case study results

Three seismic parameters including b-value, Energy Index and seismic velocity are calculated in continuous time frames of 2000 events. Because of the 90% overlap of timespans, each event is repeated in 8 to 11 consecutive spans. Event 1 in both mining sections occurred early in the year of study, hence, we do not have enough data to investigate prior to their occurrence.

The b-value is compared with ASEI and seismic velocity for Mining Section 1 in Figures 7-9 and 7-10 respectively. The event occurrence is repeated in highlighted zones called "zones of influence" for each event. For example, day 65 to day 77 is the zone of influence for Event 1 in Mining Section1. Events 2 and 3 in Mining Section 1 are 14 days apart; therefore, the overlapping days of their zones of influence (from day 219 to 238) includes both events. Similarly, Figures 7-11 and 7-12 demonstrate the ASEI and b-value variations in Mining Section 2 with two zones of influence for its two major seismic events. The spacing of the spans indicates constant high seismicity in this area. The decreased density of spans (points on the graphs) indicated less seismic activity in the area.



Figure 7-9. Variations of b-value and ASEI in Mining Section 1. The highlighted days include the major seismic events.



Figure 7-10. Variations of b-value and average seismic velocity in Mining Section 1. The highlighted days include the major seismic events.

Although there is just one span prior to Event 1, the b-value reaches its peak during the zone of influence of this event. The b-value is mostly between 1 to 1.1 for this section. There is a drastic decrease in b-value after Event 1 but it increases back to about 1.05 during a low-seismicity period (days 100 to 190). No elbow point is seen prior to the occurrence of Event 2. Prior and post vent 3; however, a slight decrease in b-value is observed. The influence zone of Event 1 includes the peak in all three seismic parameters. The Energy Index values are positive during the year of study and it jumps to more than 1 in the zones of influence of all events. A moderate reduction is observed in ASEI prior to all of the

events. The average seismic velocity rises slightly and drops after the event occurrence for all three events. The seismic velocity gradually increases from about 100 days prior to Event 2 and marginally passes the background velocity level about 15 days prior to the event. Although it seems that average velocity reaches a steady state at day 178 with no significant change in the seismicity, the rock mass contains elastic energy and is highly stressed. Therefore, Seismic Event 2 occurs. The localized seismic velocity with shorter time spans for this critical period should be calculated by seismic tomography as shown in Figure 7-11. The overlapping part of zones of influence of Event 2 and 3 encompass some moderate reductions in the b-value and Energy index. Nonetheless, the average velocity reduces after the overlap.



Figure 7-11. Variations of b-value and ASEI in Mining Section 2. The highlighted days include the major seismic events.



Figure 7-12. Variations of b-value and average seismic velocity in Mining Section 2. The highlighted days include the major seismic events.

The very beginning spans include Event 1 in Mining Section 2 from the middle of its influence zone. The seismicity of Mining Section 2 is much higher compared to Mining Section 1 and its seismic catalog includes 10 times more ray paths. The ASEI level abruptly increases by the occurrence of Event 2 after a low energy period. The b-value amount during the zone of influence of Event 2 includes an increase following a recession.

The average velocity of the rays in this section is mostly at the background level. Especially it almost remains constant at about background velocity level during the zone of influence of both events. This reveals in the entire area the high velocity and low velocity zones coexist. However, prior to the occurrence of Event 1, some reductions in seismic velocity are observed.

Both b-value and ASEI trends reveal two more seismic events in this area. Referring to Figure 7-2, two small jumps in released energy indicates the occurrence of two low-energy events at days 64 and 192. On the other hand, the catalog of seismic events in this section shows a high magnitude-low energy event on day 291 which does not show any impact on the ASEI or b-value.

Using seismic tomography, the seismic velocity can be calculated in the vicinity of mine openings prior to seismic occurrence. As shown in Figure 7-13, for a 500 m radii around

hypocenter the average velocity during each week and every three days are computed. Every three-day timeframe has a two-days overlap with its following frames resulting in daily variation calculation. This is due to the insufficient number of rays in each day for a high-resolution calculation.



Figure 7-13. Seismic velocity variations within 14 days of the event occurrences in Mining Section 1 computed based on seismic tomography in 500 m radii around the hypocenter of events. The day of event occurrence is determined as zero.



Figure 7-14. Seismic velocity variations within 14 days of the event occurrences in Mining Section 2 computed based on seismic tomography in 500 m radii around the hypocenter of events. The day of event occurrence is determined as zero.

According to Figures 13 and 14, the seismic velocity reduces in the rock mass within two weeks of the occurrence of the events. These reductions reach its maximum on the day of the event and then it increases again. All these fluctuations are subtle (about less than 50 m/s) and happen when the average velocity is up to 200m/s higher than the background velocity level. The reduction in this stage, when the rock mass is highly stressed, can be due to the dilations in the rock mass by merging the cracks and preventing the P-wave propagation. The time span and volume of interest for tomography calculation can be changed considering the number of ray paths. Table 7-2 summarizes the limits for points prior to the event occurrence as the guideline limits for future major seismic events.

Events	1-1*	1-2	1-3	2-1*	2-2
B-Value	>1	>1	>1	-	>1
Energy Index	~0	0	0	-	0
Average Velocity	-	>1% ↑	>1% ↑	-	>1% ↑
Seismic velocity around hypocent er	<1% ↓	<1% ↓	<1% ↓	<1% ↑	<1% ↓
Mining advance rate (m/w)	>3	>3	>3	-	-

Table 7-2. Limits of B-value, Energy Index, seismic velocity, and mining advance rate in dates prior to occurrence of major seismic events.

## 7.5 Discussion

As it was observed, comprehensive seismic monitoring requires measuring multiple seismic parameters. According to the observations of the case study analysis, Average Scaled Energy Index (ASEI) rises to more than one by the occurrence of a seismic event;

however, the threshold of one cannot be a precursory condition as there was no significant increase in ASEI prior to the occurrence of the events. A gradual decrease or steady-state level of Energy Index of zero prior to events is observed. Dehn et al. 2018 applied ASEI with averaging in different time frames and concluded that ASEI is a useful tool for engineers to understand the changes in relative stress in the rock mass but should be combined with other seismic parameters for better interpretation.

Based on the literature, it was expected to observe a decline in b-value prior to seismic events followed by a relative peak at the occurrences of the major seismic events (Ma et al, 2018). However, this was not a consistent trend in the b-value graphs of this study. In Event 2 at Mining Section 1, the decline occurred at the influence zone of Event 2 and the incline occurred for the close by Event 3. The reason can be the large percentage of overlap in spans in our study. The b-value is a good indicator of the changes in the seismicity of the area regarding magnitudes of the events. There are several ways for calculating b-value and the accuracy of the calculations is highly impacted by the chosen method. According to the results of this study, the typical threshold for b-value is one. When the b-value drops to lower than this threshold there might be a potential for the occurrence of a major seismic event.

The average seismic velocity of the events can be a reliable auxiliary indicator of the highly stressed zones in the rock mass. In this study, the three major seismic events in Mining Section 1 occurred when this average reaches the background velocity and marginally passes it. The background velocity level is the third threshold required for seismic monitoring and can be a potential alarm point for in-field real-time monitoring. In highly stressed zones when the seismic velocity is much higher than the background velocity level, the average seismic velocity of the events will not be helpful and seismic tomography can be used to measure seismic velocity changes in shorter time span and smaller volumes.

The seismic velocity changes; however, it might be different when the applied stress is reaching maximum and failure is close. This can be due to the dilation in the rock mass. The average seismic velocity of the events of this study based on tomography approves the laboratory test results indicating that major seismic events occur in high-velocity zones (Zimmerman and king, 1985). Moreover, it matches with studies analyzing field data specifying that major seismic events occur where induced stress is concentrated (Westman, 2004).

The seismic events occur where there is mining activity in progress. During the days that there is mining operation in progress, the seismicity of the area is changing dynamically as well. But the case study does not show s direct relation between increasing the number of major seismic events and the number of blasts per day.

#### 7.6 Conclusion

In this study, the risk of occurrence of seismic events is investigated by integrating some seismic parameters and mining advance rate. The seismic parameters include b-value, Energy Index and seismic velocity. These parameters can be used as an indicator of rock mass performance in response to mining activities. Based on the case study results, the drop of b-value below the threshold limit (one in our study) might be a potential for elevated seismic risk. Moreover, the Average Scaled Energy Index (ASEI) increases to more than the threshold of 1 when a seismic event is in progress. The seismic velocity can be measured first as the average velocity of rays associated with the seismic events. The deviation of this average velocity from the background velocity level is an indicator of high induced seismicity in the area. When the average velocity of the events deviates from the background velocity level, passive seismic tomography can be used for detailed analysis. It is observed that seismic velocity tends to reduce prior to seismic event occurrence based on the dilation hypothesis. In our case study, the seismic velocity of the area of interest declined within two weeks of the occurrence of the events.

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# **Chapter 8 - Conclusions**

### 8.1 Introduction

The potential of passive seismic tomography to indicate high stress zones and the variations in the induced stress is investigated. First, seismic tomography is applied to a synthetic block cave mine and the high velocity zones detected by seismic tomography are compared to the highly stressed zone modeled by numerical models in Examine2D software. After validating demonstrating the ability of seismic tomography to image high velocity zones, a case study in a narrow-vein mine is considered to apply seismic tomography in a back analysis process to investigate the post- and pre-event changes in the seismicity and seismic velocity of rock mass. The first step in the case study is to identify if there were any significant changes in seismic velocity prior to occurrence of significant seismic velocity in the days prior to the occurrence of major seismic events. Then shorter time frames were considered to investigate minor changes in seismic velocity. Finally, the velocity variations are integrated with seismicity, Energy Index, and mining rate to evaluate a protocol for occurrence of a major seismic event which could be used by mine engineers during mining operation as safety alarm limits.

#### 8.2 Summary of observations

Passive seismic tomography provides an indirect measurement of induced stresses in the rock mass; this dissertation presents findings from a numerical simulation at a block cave mine and key findings from analysis of seismic data at a deep, narrow-vein mine. In the framework of a block cave mine, this information can assist in the safe extraction of the ore by operational controls. As a result, high-stress zones are in line with the high-velocity zones measured via the synthetic ray paths in a numerical block cave mine model. It is observed that seismic tomography using the SIRT algorithm has high potential to monitor induced stress distribution in block cave mines.

The seismic velocity at a deep narrow-vein mine was investigated for weekly time intervals in order to test the hypothesis of consistently increasing induced stress near hypocenters of major seismic events. The weekly analysis of seismic wave velocity variations shows about up to 2.1% decrease in the week prior to the event. Based on this analysis, the hypothesis that the P-wave seismic velocity would continually increase at the hypocenter of events is not observed for these events at this mine. A potential reason that the hypothesis was not supported by the data is that new fractures may be developing within the highly-stressed rock mass, resulting in either no increased velocity or a reduction in velocity at the hypocenter prior to the seismic event.

General consistency was observed in the high-velocity zone's location and magnitude weekly. The volumetric extent and peak magnitude of these zones, however, was not identical prior to and after each event. The hypocenter of all the three major events occurred at the edge of a high-velocity zone rather than at the center of the zones. The higher deviatoric stress levels near the edges of the zones compared to the center of the zones may cause the deformation initiation at the edge of high velocity zones. Therefore, when observing a high-velocity zone in tomograms, there is a strong potential for the subsequent event to locate somewhere along the edges of the zone.

The pattern of energy release was different in each of the three events, which may be due to the different failure mechanism (which this study did not investigate). Events 1 and 3 occurred suddenly followed by several minor events, while Event 2 triggered fewer subsequent minor events but was followed by a major event 17 days later.

According to the daily difference analysis, it was observed that for three of the five events, there was no significant change (more than 1%) in seismic velocity within 200m of the hypocenter in 6 days prior to the events. However, the velocity difference was detectable (more than 1%) within 200m of the hypocenter on the day of all five events. The subtle changes were probably due to the result of the dilation during the plastic failure of the rock mass, when the applied pressure is reaching to its peak and new fractures are merged.

The investigation of the blast rate in three of the events with Es/Ep of less than 5, did not show any persistent trend in seismic velocity changes correlated to blasting. However, all these three events occurred when there were at least three blasts within a week of their occurrence. The random high-velocity zone could be induced and destressed after blasting but there was no predictable trend in their advent.

In order to have confidence in the observed results, it is necessary to understand the uncertainty associated with the results. One assessment of the uncertainty is the error location of the events which were used as the input data for the analyses. For this data set from the deep, narrow-vein mine, the event locations were provided with the data set and not determined as part of this study. The mean location error for all events was 31m, which is 67% of the 45m radius used for the weekly velocity change analysis. As shown in Figures 4-10 through 4-12, the weekly velocity change analysis shows a consistency and repeatability of the tomographic results which is significant considering that each of the tomograms was developed with a completely unique dataset. Another quantitative measure of variation was found using the bootstrapping (or jack-knifing) method. With this method, selected weekly tomograms were run multiple times, each time removing 10% of the data, and the resulting velocity of about 0.5% (44m/s) which is less than the average velocity change observed for the weekly analyses, as shown in Table 6-1.

The seismic parameters, including b-value, Energy Index and seismic velocity, can be used as an indicator of rock mass performance in response to mining activities. Based on the case study results, the drop of b-value below the threshold limit (1.0 in our study) might be a potential for elevated seismic risk. Moreover, the Average Scaled Energy Index (ASEI) increases to more than the threshold of 1.0 when a seismic event is in progress. The seismic velocity can be measured first as the average velocity of rays associated with the seismic events. The deviation of this average velocity from the background velocity level is an indicator of high induced seismicity in the area. When the average velocity of the events deviates from the background velocity level, passive seismic tomography can be used for detailed analysis. It is observed that seismic velocity tends to reduce prior to seismic event occurrence based on the dilation hypothesis. In our case study, the seismic velocity of the area of interest declined within two weeks of the occurrence of the events.

#### 8.3 Conclusions

As demonstrated by the results of this study, passive seismic tomography is a promising tool to improve our understanding of the behavior of rock mass and engineering a system to actively monitor its performance. This will help mine engineers to improve the safety of the miners and optimize production. The high velocity zones correlated to highly stressed areas can be reliably detected by passive seismic tomography and the hypocenter of events are expected to occur at the edge of high velocity zones.

In four out of five cases, a velocity decrease (dilation) in the week before a seismic event around hypocenter of the events was observed and in three out of five cases, a decrease of velocity greater than 1% within 200m of a hypocenter on day of the seismic event was observed. It is therefore inferred that the stress is not increasing at the point of eventual failure in the weeks prior to the seismic event, and so the rock mass is possibly behaving plastically not elastically. Although major seismic events typically occur in a high-velocity (highly-stressed) location, but at the hypocenter the rock mass is behaving plastically and likely dilating in the days and/or weeks prior to the event.

#### 8.4 **Recommendations for Future Work**

The passive seismic tomography results may also correlate with different rock types; however, the geology of the mining sections was not available for this study. It is recommended to overlay the details of the rock types to the results of this study both in two-dimensions and three-dimensions. This correlation can also get updated with exploration geological maps and also the drilling updates about rock types. In addition, the type and strength of explosive in the blasts can be monitored and correlated with seismic velocity changes. On the other hand, the mechanisms of the events can be checked if the waveforms are available.

Secondly, it is recommended to apply template matching to the seismic data in order to find more minor events with smaller magnitudes within the volume of interest. This method has been applied in seismology for earthquakes and can be similarly apply to mining-induced seismicity. This method is similar to the texture analysis in image processing and can increase the number of rays per voxel which will enhance the reliability of seismic velocity tomography. Moreover, the uncertainty of calculations can be evaluated and improved using different methods other such as checkerboard test.

Thirdly, in this study the Energy Index and B-Value were computed for the entire rock mass area including the voxels away from the both mining sections. For future studies, the volume of interest can be localized to the mining section area. This might eliminate the influence of the noises and further operations.

Finally, the method of seismic wave velocity variations and correlation of its changes with other seismic parameters such as B-value and Energy Index can be applied to other hard rock mines with different mining methods such as sublevel caving and shrinkage stopping. As the mining practices are different in different methods and the distribution of low and high velocity zones might vary by mining methods. For instance, the filled material in cut and fill changes the seismic wave velocity compared with the surrounding rock mass.