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Imaging of temporal stress redistribution due to triggered seismicity at a deep nickel mine

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HIGHLIGHTS

- Major events are associated with stress evolution at underground mines.
- Major events tend to occur in highly-stressed regions.
- Stress concentration and stress relief coexist in close proximity.
- Double-difference tomography can improve locating mining-induced seismicity.

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ABSTRACT

We conducted three-dimensional passive seismic tomography surveys by using mining-induced seismicity of a deep nickel mine. To investigate the stress evolution with the distribution of major events, we collected location information of monitored seismicity and arrival time picks of waves transmitted from seismicity at the Creighton Mine in Sudbury, Ontario, Canada to produce velocity tomograms. From June 22nd to July 24th, 2011, four major events (moment magnitude >1.0) were observed associated with 13 630 microseismic events. We developed a large model and a small model, referring to scales of grid spacings and areas of territory, for double-difference tomographic inversion. The large model was used to examine the general trend of velocity distribution before and after the major events; the small model with finer grid spacing gave rise to a higher resolution to show results in detail. Seismic imaging results of velocity distribution showed good agreement with major events in different regimes, implying that the stress evolution was consistent with major events in the surrounding rock mass. By comparing the results obtained from tomographic inversion, we found that the stress in the region near major events started increasing before major events. High-stress areas, indicated by high-velocity anomalies, appeared and expanded adjacent to the region with major events.

1. Introduction

Ground fall is the leading cause of injuries in underground mines, especially at great depth. Ground control issues accounted for over 40% of fatal accidents at underground metal mines in the USA between 2008 and 2012 (MSHA report,[1]). Reliable ground control with seismic hazards mitigation is an essential consideration in mine safety. To mitigate seismic hazards, predictive analyses are necessary to assess the seismic potential leading to failures in rock masses. Specifically, seismic hazard analyses require identification of anomalously high stress associated with seismicity in mines. We use the term “major event” to refer to a seismic event that has a moment magnitude larger than 1.0. Studies have concluded that

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seismicity distributes along significant fractures in the mine sites and stress inversions from seismicity are consistent with in-situ measurement of stresses.[2] Investigating the relation between mining-induced seismicity and stress distributions is facilitated by seismic tomography, which has been widely applied for imaging and mapping Earth's sub-surface characteristics.[3] Seismic tomography has developed rapidly from a technique devoted to understanding natural earthquakes to a greatly useful technique used in the mining industry. Under the framework of safety analyses for earthquakes, how to apply seismic arrays to improve mining processes were studied.[4,5] Further, studies have proved seismic tomography as a predictive tool for stress measurement of rock mass body.[6,7] It allows for an estimation of stress distribution remotely and noninvasively by examining seismic images, which are generated using information from mining-induced seismicity.

Rock physics studies found and validated that seismic events are important precursory signatures of rock failures.[8] Lab tests confirmed that wave propagation is hindered by microcracks.[9] Associated with the development of microcracks, seismicity is triggered as a sign of strain energy release. Pressures orthogonal to the direction of microcracks tend to close the fractures, which reduce the velocity of wave propagation in the rock mass, and therefore cause a rock healing effect to reinforce wave propagation. Considerable lab studies have indicated how the change of stress fields affects velocity of wave propagation in rocks. Mavko et al.[9] concluded that the velocity at which a seismic wave travels through a rock mass relates to the applied stress. Velocity tomograms were used to infer the stress redistribution of an underground mine with extending the knowledge from lab studies into an underground mine.[10] By imaging the velocity structures of rock mass in underground mining, Westman et al.[11] studied the stress redistribution related to mining-induced seismicity to interpret the mechanisms of ground failures. Several studies have revealed that high-velocity anomalies in the passive tomography are associated with high seismic activity zones in the longwall mining.[12–14] In the block cave mining, time-lapse passive tomography was used to infer the cave geometry and its evolution through time.[15,16] However, previous studies limited their targets to clusters of microseismicity. The effects of stress conditions on major events in mines need to be further investigated because the stress distribution plays a significant role in the occurrence of major events in underground mines.

The goal of this work is to investigate change of the stress distribution associated with the occurrence of major events in a hard-rock underground mine using double-difference tomography. A full coverage of seismic monitoring system and high seismicity rates in this mine enable good quality data sources to infer stress distribution in the seismically active regions at this mine. Results provide significant clues to the distribution and the evolution of stress with the occurrence of major events. Temporal changes in the velocity structure reflect the stress distribution evolving through time and its response to major events. Specifically, significant tendency of the stress change before the major events is able to provide insights to forecasting major events and mitigating seismic hazards.

2. Data and methods

Data sets of mining-induced seismicity and major events were recorded in Creighton Mine of Sudbury, Canada, which is a hard-rock underground mine with the majority of seismicity due to the great depth and major seismically-active structures.[17] Creighton Mine has used a variety of mining methods over the course of its mine life in history. Since 2008, it has adopted a large-diameter blast holes method associated with vertical retreat mining. The depth of main production areas ranged from 1829 to 2348 m.[18]

Seismic events, arising from strain energy previously accumulated in the rock, are the sources to generate tomographic images of the velocity distribution.[7] After collections of arrival time picks of mining-induced seismicity, we performed tomographic inversions to generate tomograms to show the velocity distribution during each target regime. Then, the stress distribution could be inferred by adopting velocity–stress relations. That is, high velocity bodies represent stress concentration; In contrast, low velocity bodies reflect stress relief regions.[19] Arrival times from microseismic events were recorded by multiple sensors installed in a microseismic monitoring system, which was deployed to capture small events measuring -3 Mw (Moment magnitude) to $+1$ Mw. This microseismic monitoring system, developed by ESG solutions, was consisted of 10 triaxial sensors and 52 uniaxial sensors. Triaxial sensors contributed to high accuracy when calculating source parameters (magnitude, energy, source radius and apparent stress), and source mechanism analysis, because ground motions at each sensor location were recorded in three directions. Additionally, uniaxial sensors were more cost-effective and available in greater density, providing higher source location accuracy and magnitude detectability. The depth of stations ranged from 1508 to 2392 m, ensuring a good coverage on the rock masses adjacent to main production areas. In addition to monitoring microseismicity, how to record major events is an important task as well. At Creighton Mine, major events were recorded by a strong ground motion system, which was installed on the ground surface and designed to capture large-magnitude seismicity (up to $+4$ Mw) related to mining operations. To guarantee the coverage on a full magnitude range of seismic events, it is crucial to have the combination of these two systems. We analyzed 188 250 arrival times of P-wave from 13 630 microseismic events, the depth of which approximately ranged from 1450 to 2700 m, occurring from June 22nd to July 24th, 2011 at Creighton Mine. These data, in conjunction with the locations of events and stations, were input for tomographic inversions. By manifesting the velocity distribution in tomograms, we compared the velocity change before and after the period including all major events (Table 1).

Velocity tomography allowed us to assess the change of stress distribution over space and time at Creighton Mine. We were capable of identifying the corresponding distribution of stress of the rock mass by examining the velocity distribution in tomograms. It is well known that mechanical properties of rocks are significantly