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Preconditioning blasting for a deep blind sink shaft excavation

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Abstract

In 2024, Glencore successfully completed an internal winze from 1,150–2,635 m below the surface at Craig Mine in Sudbury, Ontario, Canada. The shaft was sunk in brittle hard rock, which at the depths of construction resulted in seismicity, stress fracturing, pervasive spalling, and rockbursting conditions. The high-horizontal in situ stress meant adverse conditions manifested both in the shaft walls and the bench face. For comparison, a typical lateral development round throws muck away from the face, leaving it partially unconfined and this allows for stress redistribution to occur immediately after the blast. On the other hand, blasted muck from a shaft blast will fill the void created, which confines the bench and inhibits large-scale stress fracturing from occurring. As confinement is reduced from mucking out the round, there is an increase in strainburst risk when operators are required to mark bootlegs and prepare for drilling/loading the next advance. Due to the limited working area associated with a shaft sinking operation, development is highly dependent on physical labour and handheld mining equipment. Compared with lateral mechanised development, fewer tactical controls can be used while shaft sinking to mitigate the risk of rockburst to operators. Preconditioning blasting became a critical control for managing high stress conditions in the shaft sink. There are limited guidelines in published literature for preconditioning blasting in shaft sinking operations and less evidence that preconditioning is providing a benefit. A customised preconditioning blasting strategy was developed based on visual inspections, seismic monitoring, and numerical modelling. The number of holes and location of the 'de-stress' charges were adjusted according to the rock mass conditions. It was also essential to institute controls on the shaft bottom mucking to prevent mucking beyond the planned break, so that the stress-fractured material that confined the highly-stressed rock ahead of the bench face was not removed. The experience learned from this project should be beneficial to other future shaft sinking projects at depth.

Keywords: *preconditioning blasting, de-stress blasting, strainburst, deep mining, shaft sinking, winze*

1 Introduction

In 2017, lateral development began from the existing Craig Mine infrastructure to the location of the new internal winze 1.2 km away, which was used to access the Onaping Depth deposit. The shaft was sunk using two different methodologies: raise-and-slashing and conventional blind sinking. Due to the long duration required to build the material handling infrastructure, two inline 3 m diameter raises were pulled from 1,915–1,455 m and 1,440–1,150 m, then slashed to a minimum 7.8 m diameter. By using this methodology, the shaft could advance with blasted muck collected at the bottom of the raises while concurrent construction was occurring at the top of the winze. Once the sinking reached the 1,915 m level, the methodology changed to a conventional blind sink to the bottom of the shaft at 2,635 m. Figure 1 presents an overview of the Craig Mine complex, showing the locations of the sinking methodologies. This paper focuses on the blind sink completed for the Onaping Depth winze; however, details for the shaft slash can be found in Hall et al. (2021, 2024).

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Due to the extreme depth of this excavation, potential strainbursting was anticipated throughout the shaft sink. Compared with typical lateral development, fewer risk mitigation tools can be used when strainbursting conditions are encountered in a shaft sinking operation due to the confined working area at the bottom of a shaft. In addition, when the shaft sink begins it cannot deviate from its trajectory when adverse conditions are encountered. The main tools available to deal with strainbursting conditions in a shaft are dynamic ground support, preconditioning blasting, and (in some cases) bringing the concrete liner as close to the bench face as possible. In general, preconditioning blasting is not well understood (Miao et al. 2022) or well documented, and therefore further investigation was required because it was considered a critical control.

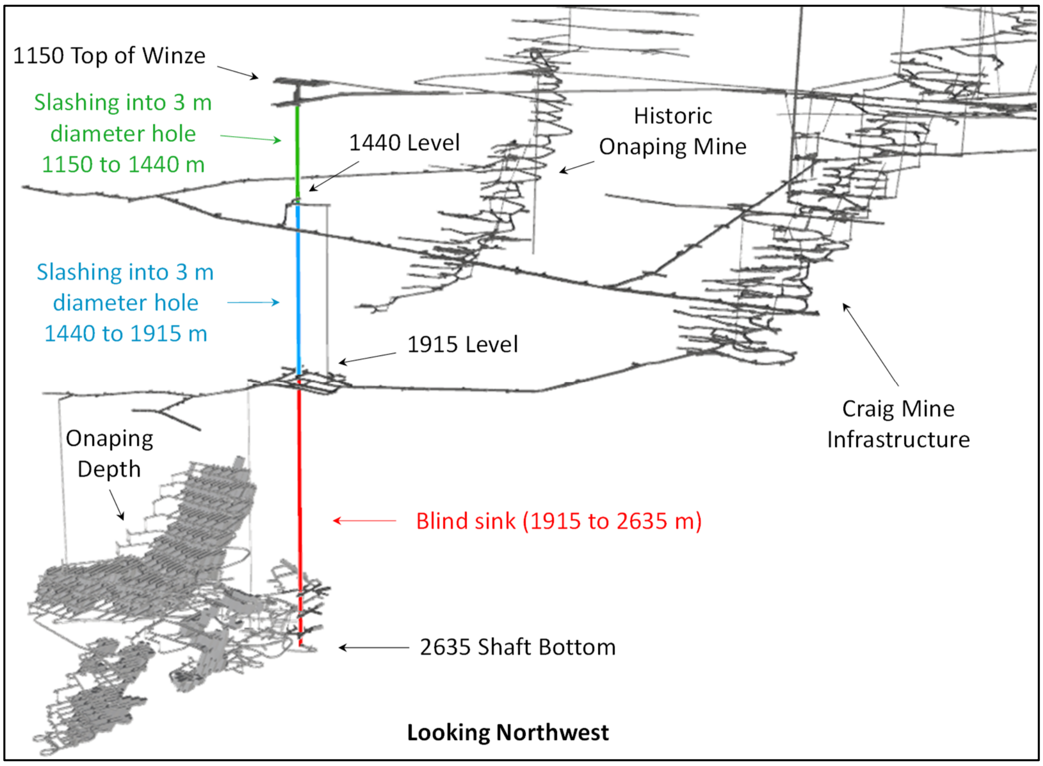


Figure 1 Image showing an overview of the Craig Mine complex and the locations for two sinking methodologies

Preconditioning blasting has been used for decades in highly-stressed grounds to prevent and mitigate strainbursts in the area around an advancing mining face. Preconditioning blasting refers to the detonation of explosives ahead of a mining face to reduce the potential for strainbursting and the associated seismic activity. The goal of preconditioning blasting is to generate a zone of fractured rocks ahead of the excavation because fractured rocks have a limited ability to store strain energy compared with more intact rock. A precondition blasted zone creates a buffer region of damaged rock ahead of the excavation, causing high stresses to be pushed deeper into the rock mass further away from the excavation boundary (Roux et al. 1958; Toper 2000, 2003).

There have been several studies on preconditioning blasting in lateral development headings dating back to the 1950s when face preconditioning was trialled to mitigate rockbursting in deep South African gold mines (Roux et al. 1958). The goal was to extend and deepen the existing zone of fractured rocks surrounding the excavation in order to push stresses deeper into the rock mass. These efforts were concluded to be successful based on a reduction in the frequency of rockbursts. More recently, there has been several studies that have tried to quantify the overall success of preconditioning blasting in South African gold mines by examining seismic activity and intensity of rock fracturing (Sengani & Zvarivadza 2019; Andrews & Sengani 2017; Toper 2000, 2003). Based on seismic analysis, it was found that there were more smaller magnitude events and fewer larger damaging events when preconditioning was used, indicating a more controlled propagation of fracturing. Using ground penetrating radar, preconditioned faces were observed to have an increased density of fracturing ahead of the face. Vallejos (2022) described similar trends in seismicity when preconditioning was used at Codelco's El Teniente Mine in Chile. However, it was detailed that with too much preconditioning efforts there was a detrimental effect due to the inability to drill the subsequent rounds of preconditioning holes because of the collapse of holes in over-fractured grounds.

There is less information available detailing preconditioning blasting for vertical development. Redpath (1972), briefly noted that three 4.8 m long preconditioning blastholes were drilled ahead of the bench face to mitigate bursting conditions during the sinking of Inco's Creighton No. 9 shaft in Sudbury, Ontario, Canada, which was sunk in 1969 to a depth of 2,176 m. Dickout (1962) described drilling two preconditioning blastholes 45º down into the walls while sinking Creighton's No. 11 shaft, which was sunk to 1,782.5 m. No holes were drilled into the bench face. Blake & Hedley (2003) described using two preconditioning blastholes in the walls and four in the bench face while sinking the No. 3 shaft at Macassa Mine in Kirkland Lake, Ontario, Canada, which was completed in 1986 to a depth of 2,225 m. According to one of the leading shaft sinking contractors in the world (Price-Jones, pers. comm., 2018), since the 1990s shaft sinking preconditioning blast design has followed the four-hole layout presented in Figure 2. Qualitatively there appeared to be fewer rockbursts when this preconditioning blasting was used, however, these studies have limited quantifiable evidence to support the benefit of preconditioning blasting.

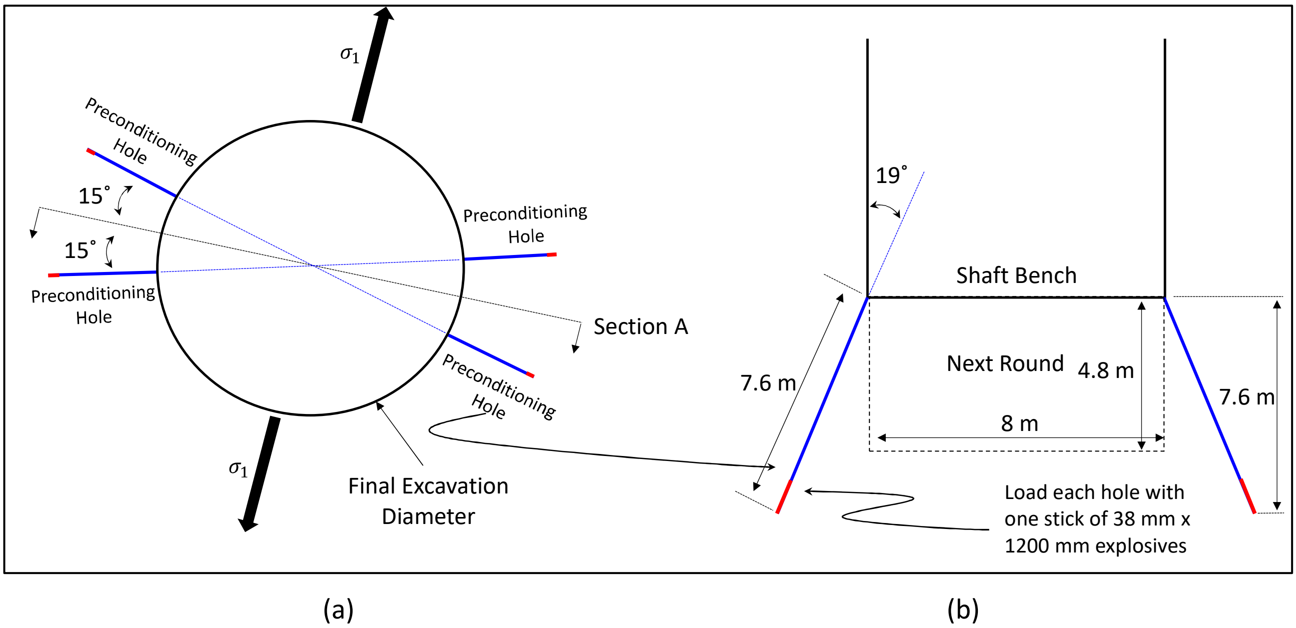


Figure 2 Modern preconditioning blast layout for shaft sinking in high-stress ground. (a) Plan view; (b) Section view (Price-Jones, pers. comm., 2018)

Whether for lateral or vertical development, there are no empirical guidelines present in the literature for preconditioning blast design. Given the wide range of physical properties present at individual mine sites such as rock mass strength, stress orientation and magnitude as well as the size and orientation of an excavation, it is unlikely that a single preconditioning blast design will provide the same benefit from site to site or have any positive effect at all. For that matter, preconditioning blasting could be detrimental by damaging the rock around the planned ground support or by pinching stress closer to the excavation. There is also limited information available to evaluate the success of the preconditioning blast. For these reasons, a preconditioning blast strategy was independently developed for the sinking of the Onaping Depth winze constructed within Glencore's Craig Mine.

2 Seismicity in shaft development

In a lateral development round, blasted muck is thrown away from the face leaving the back, a portion of the walls and the face unconfined. Due to the lack of confinement, the rock can redistribute stress. The stress redistribution manifests as a spike in the seismic event rate occurring immediately after the blast and tapers off after the first few hours. The elevated seismicity after the blast is associated with fracture creation, fracture propagation, active spalling and small strainbursts occurring in the unconfined areas of the blasted round. In the immediate time frame after the blast, there are no operators present in the area and therefore there is limited risk from this seismic activity.

A shaft blast has a significantly different seismic response compared with a lateral round due to the vertical geometry of the shaft excavation. The blasted muck is thrown vertically and then falls back into the void that was created, which then provides confinement to the floor and walls. As a result, the rock below the muck pile has a limited ability to fracture until mucking begins which is when operators are present. The mucking cycle for the Onaping Depth shaft took 24 hours on average for a 3.8 m-long round, which included time for bolting the walls. Due to the limitations of using handheld mining tools, a maximum height of 1.5 m of unsupported wall was exposed at any given time. The slow incremental exposure of the walls and installation of 2.4 m-long dynamic bolts limited the ability of the rock in the walls to dilate, actively spall or burst. However, as proximity to the bench decreases there is a significant loss in confinement over a large area on the bench, which then allows the rock to be further strained and develop a failure zone ahead of the face associated with an increase in seismic activity, active spalling, and strainbursting.

Before beginning the blind sink, 17 microseismic sensors were installed ahead of the planned shaft, which provided sensitivity to moment magnitude −2.0 to −1.8 throughout the shaft sink. Having this level of sensitivity was critical for monitoring the rock mass response while sinking. Figure 3 presents the event rate graph for two typical drill-blast cycles while sinking through norite early in the blind sink at 2,000 m, which highlights the increase in seismic activity as the bench is exposed. No preconditioning blasting was used in either of these cycles. Observations made using the seismic monitoring system and field visits showed minimal seismic activity while mucking and bolting. However, there was a significant increase in seismic activity as the bench was approached within 0.5 m and exposed, which is indicated in the red-dash-line-marked windows. The event's moment magnitudes as the bench was exposed were typically less than MW−1.0; however, it was often accompanied by the ejection of small shards of rock and bulking of rock in the floor.

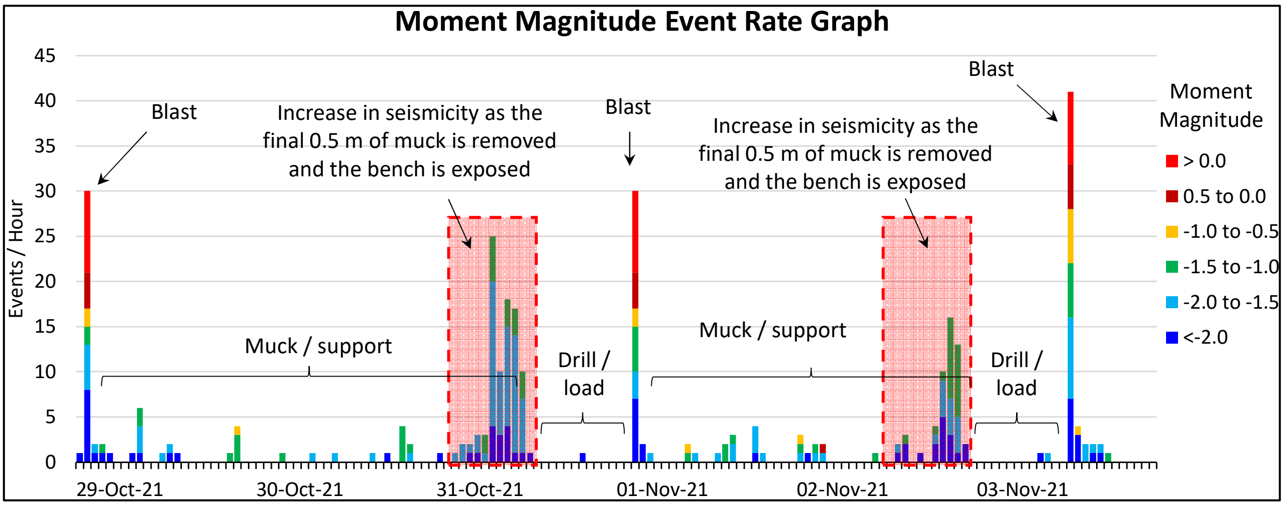


Figure 3 Event rates of seismic activity in the blind sink development cycle

Having the seismic array in place to monitor the shaft sink allowed the engineering team to identify the time in the cycle when risk is the highest for the operators, which coincided with exposing the bench face. This detail has not been documented in the literature previously for a shaft sinking operation. Bolting and screening the bench face is not a viable control because there is ongoing seismic activity as the final muck is removed from the bench. Therefore, the most viable and practical means of managing the seismic activity on the bench face is preconditioning blasting.

3 Developing a preconditioning blast strategy in norite

After reviewing the modern preconditioning blasting pattern presented in Figure 2, there was some doubt about the overall effectiveness of the proposed pattern from a technical standpoint as well as some concern from a health and safety perspective for the operators. From a technical standpoint, the toe of the preconditioning holes would be located 2.47 m into the wall where there are high levels of confinement in the rock mass. Due to the high confinement and a lack of void for broken rock to bulk into, it is difficult for fractures to extend far from the preconditioning blast and generate a sufficient volume of preconditioned rock. Any fractures that are created will likely slam shut immediately after the high-pressure blast gases dissipate. Once the fractures have been closed, stress can flow through the fractures similar to stress flowing through a healed joint set, which would result in limited preconditioning benefits. Although the toe of the preconditioning holes is designed to be beyond the 2.4 m long ground support, there is potential to intersect undetonated explosives due to various factors such as hole deviation and overbreak on the walls. Therefore, from a health and safety perspective drilling preconditioning holes into the walls presented a risk to the operators and was not pursued.

In order to develop a preconditioning blast design for the Onaping Depth blind sink, an understanding of the rock mass characteristics and stress conditions is required so that high stress areas can be identified and targeted. The blind sink began in norite, a fine to medium grained igneous rock characterised as strong and brittle with widely spaced and long planar/persistent joint sets. Based on lab testing, the average uniaxial compressive strength of norite was found to be 225 MPa. The maximum principal stress orientation at Craig Mine is approximately 105° off north or roughly east–west. This resulted in higher stresses on the north and south walls of the shaft, where there was increased depth of failure and seismic activity, while the east and west walls displayed minimal signs of stress damage (Figure 4). Due to the significant depth of the shaft, the expected stresses resulted in a stress-to-rock-strength ratio of 0.56–0.72 which is favourable for heavy rockburst conditions according to Brown & Hoek (1980).

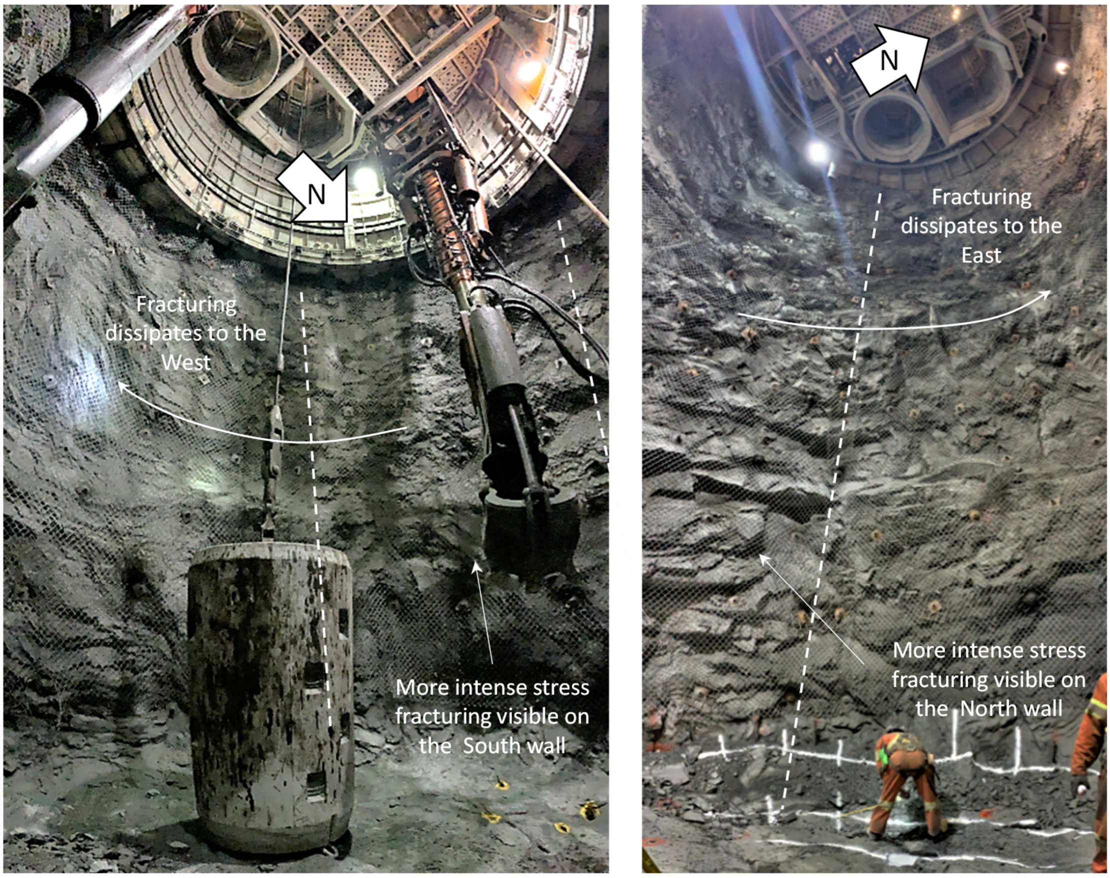
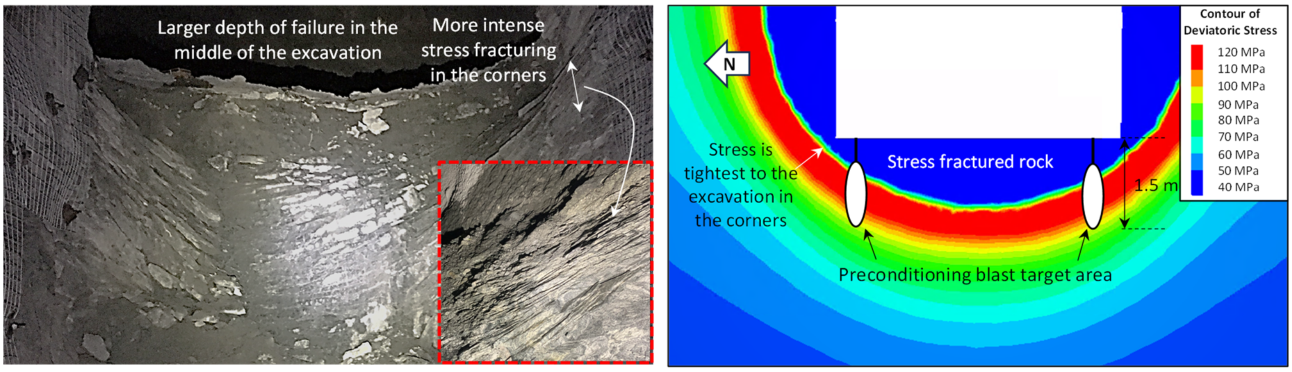


Figure 4 Stress fracturing visible on the north and south walls of the shaft (Hall et al. 2024)

Benching in lateral development headings in various areas of Craig Mine in norite provided an excellent opportunity to observe the extent of stress fracturing formed in the floor when the original pilot drift was excavated. An image of stress fracturing visible while benching on the 1,150 level is presented in Figure 5a. The stress-fractured area, which has limited ability to carry stress, is important because it gives insight into what is occurring below the shaft bench. The stress fractures take on a concave shape below the bench with a thin zone of dense stress fractures at the corners transitioning to a deeper depth of failure with wider spaced fracturing in the middle of the drift. Based on the data collected, numerical models can be generated to help understand the stress conditions.

The depth of the preconditioning holes is another important factor to consider for a preconditioning blast. If the holes are too shallow the preconditioning blast will miss the intact high stress ground and further damage the stress-fractured rock, making drilling the subsequent round challenging. If the preconditioning holes are too deep, the high confinement ahead of the bench face will suppress the ability of blast fractures to grow and create a destressing effect. Destressing can only initiate when the rock mass experiences a loss of confinement, allowing the fractures to expand and dilate. Based on the observations made while benching and from simulated numerical models, the north and south corners of the shaft bench were targeted for preconditioning, which is where stresses are tightest to the excavation. Figure 5b presents a section view of a numerical model contoured with deviatoric stress outlining the target area for the preconditioning blastholes.

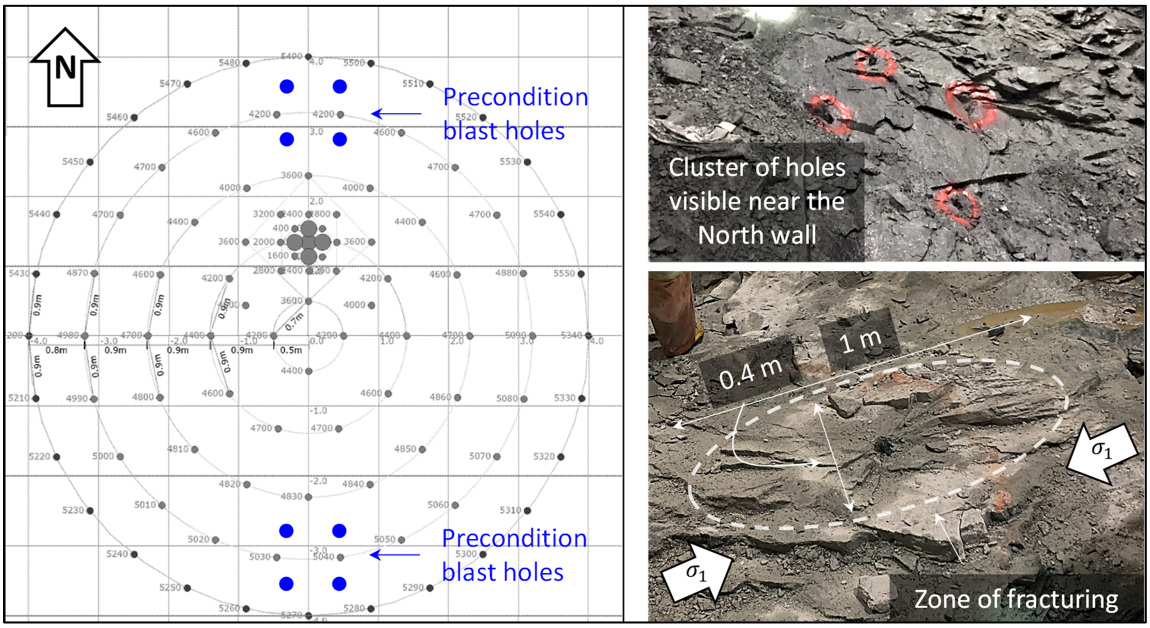


(a) (b)

Figure 5 (a) An image of stress-fractured floor exposed while benching; (b) North–south section of the shaft simulated with numerical modelling

Figure 6a presents a plan view of the preconditioning holes in the blast pattern. Two clusters of four preconditioning blastholes (eight total) were used to precondition the north and south corners of the bench. The individual holes, drilled vertically, are spaced 0.7 m from one another. Based on previous work, with high levels of confinement, a preconditioning blast can have fractures extending a maximum of 16 blasthole diameters in the direction parallel to the maximum principal stress (Andrieux 2005; Cullen 1988; Scoble et al. 1987). The shaft used 44 mm diameter holes, therefore there was potential to have 0.7 m of fracturing extending away on either side of the hole. The four-hole cluster intends to have some fracture connectivity between each hole such that there is a larger volume of rock damage and fracturing. The preconditioning holes were drilled 1.5 m beyond the planned round length on the edge of the stress-fractured and intact rock zone (5.3 m-long preconditioning holes for a 3.8 m-long round). The preconditioning blastholes were charged with 0.99 m-long 40 mm diameter Senatel Magnafrac packaged emulsion (1.14 g/cc density and 5,000 m/s velocity of detonation). When tamped (compressed into the hole) the charge length was 0.8–0.85 m-long with the remainder of the hole filled with gravel stemming. Without stemming, damage to the rock is minimal because the majority of the energy is lost out of the hole; therefore, stemming is critical for preconditioning blasting. The preconditioning holes are detonated first in the sequence before any of the other holes from the main body of the round. Overall, for a 3.8 m-long round with 117 blastholes at 44 mm diameter, only 1.4% of the total explosive is dedicated to preconditioning. After each blast, the pattern of holes was rotated 45° to avoid drilling through previous holes. It should be noted that no preconditioning holes were positioned in the walls. Perimeter holes were charged with bulk explosives (not with decoupled products) to release more energy into the wall and generate a deeper fracture zone.

Several observations were made when the preconditioning holes were exposed on the bench. In general, there was significant cratering of the holes up to 100–200 mm diameter. Camera surveys of the holes found both vertical and horizontal fracturing with the more intense fracturing visible near the top of the holes where there was less confinement. Depending on how much of the charged length of the hole was exposed, a cross-section of damage could be seen. When this occurred, two to five fractures extended up to 1 m in the orientation parallel to σ_1 and two to three fractures extended up to 0.4 m in the orientation perpendicular to σ_1. The volume of fractured rock may not appear significant; however, it is likely to interrupt the flow of high stresses at the corners of the bench without damaging the rock mass to the point that drilling and loading became a significant challenge. Images of the fracturing can be seen in Figure 6b.

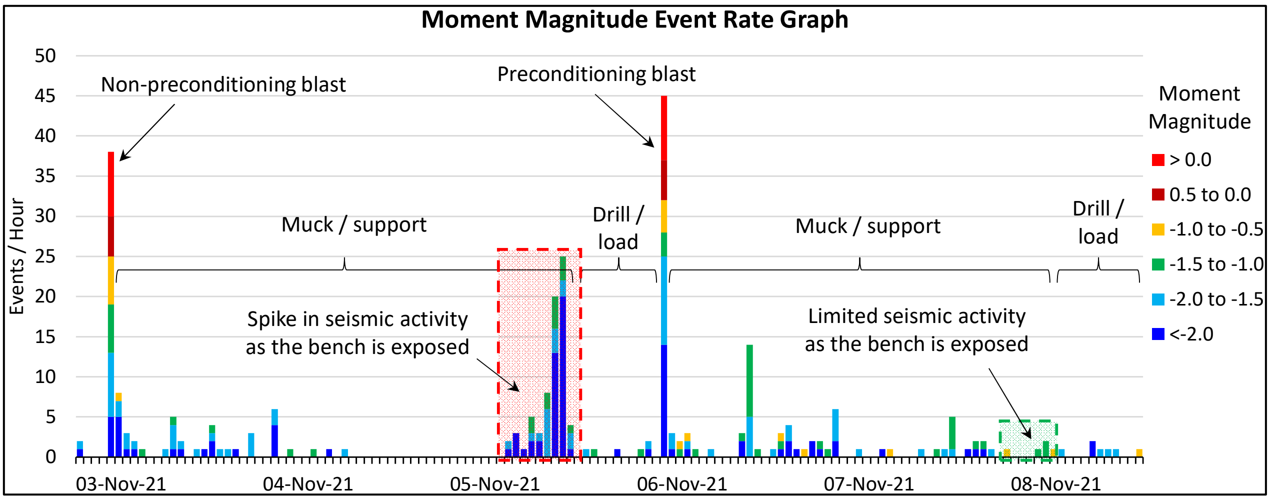


(a) (b)

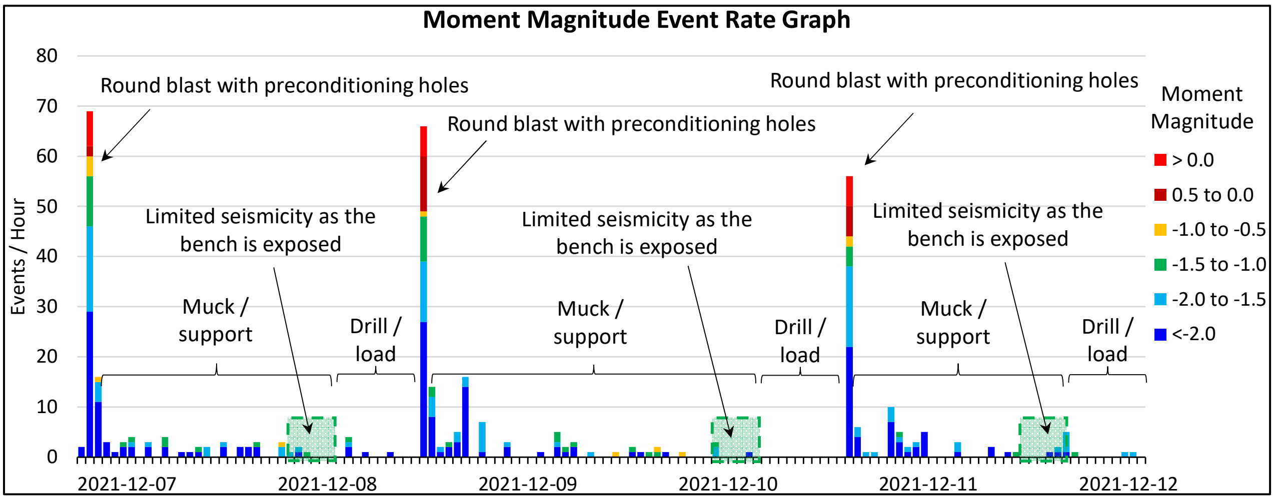
Figure 6 (a) Plan view of the preconditioning pattern that was used while sinking through norite; (b) Observations of holes on the bench

A preconditioning blast trial was planned to evaluate the blast design early in the blind sink. Although the trial was initially to be limited to 12 blasts total, the benefits of the preconditioning blast led to standard implementation. In total, 50 shaft blasts were examined, with 17 non-preconditioned and 33 preconditioned. The trial began 60 m below the 1,915 m, where the shaft was away from the influence of the 1915 level construction activity and ended at 2,150 m. The sensitivity of the system was good during the trial with MW-2.0 events consistently recorded. The entire preconditioning trial was completed in norite.

Several seismic parameters were evaluated during the trial to examine the effectiveness of the preconditioning blast. These included the number of events, event size, energy index, and apparent stress. The most notable measurable difference between preconditioned and non-preconditioned blasts is the limited number of events that occurred as the final 0.5 m of muck was removed from the bench when preconditioning blasting was used. The average number of seismic events was reduced by more than half from 129 to 66, while the average maximum moment magnitude seismic event that occurred for each blast was reduced from −0.4 to −0.7 when preconditioning blasting was used. Figure 7a presents the seismic event rates for a blast that did not use preconditioning and a blast that used preconditioning, while Figure 7b presents the event rates for three blasting cycles that used preconditioning blasting. When preconditioning blasting was used, there was a small increase in the number of events that occurred with the blast, although the exact number of events was difficult to determine due to the detonation of caps, boosters and the charged column. Qualitatively, the operators on the bench noted that when preconditioning blasting was used, no material was ejected from the bench, and there was a significant decrease in seismic activity as the bench was exposed. The seismicity that did occur seemed to be deeper in the floor with limited vibration felt in their feet and legs.



(a)



(b)

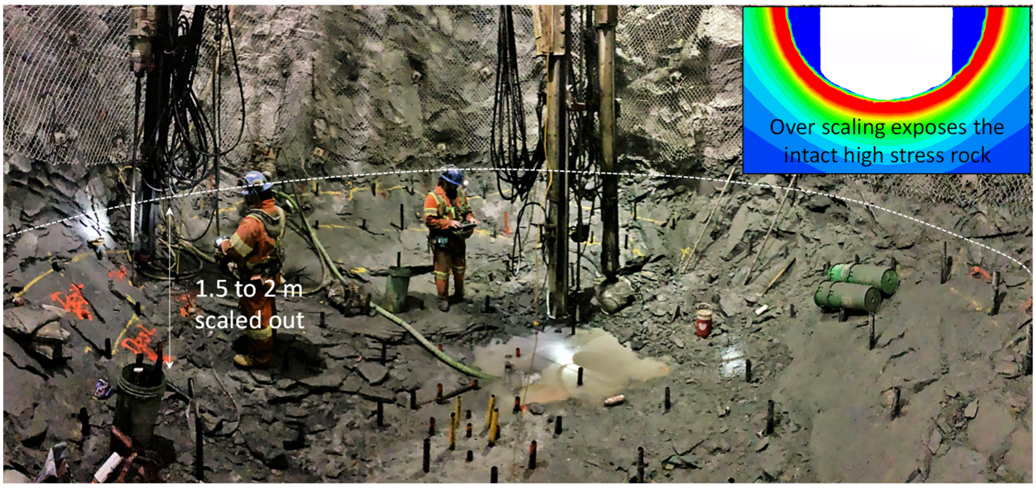
Figure 7 (a) Seismic event rate for a non-preconditioned blast cycle and a preconditioned blast cycle; (b) The distribution of seismic event rates in a three-blast cycle with preconditioning blasting

Although the averages show a favourable preconditioning outcome, it should be noted that the rock mass is variable and there can be outliers within the group. For example, the maximum number of events that occurred in preconditioning and non-preconditioning blast cycles were 237 and 288, respectively, while the maximum moment magnitudes for preconditioning and non-preconditioning blast cycles were 0.5 and 0.7, respectively. Overall, there was generally a reduction in seismic potential when preconditioning blasting was used. Based on the seismic data, it is seen that preconditioning blasting is most effective in reducing the number of events that are less than MW−1.0, which were associated with small ejection sof material from the bench. It should be noted that a single MW−1.0 event may have been downgraded to multiple smaller events that were not large enough to be recorded by the microseismic system; nonetheless, there was a more passive release of seismic energy when preconditioning blasting was used.

Between 2,155–2,260 m the shaft sink crossed two transitional lithologies: dark norite breccia (190 MPa) and late granite breccia (260 MPa). While sinking through these lithologies, the preconditioning strategy remained in place with no change to the design. These rock types were blockier and had minimal seismic response compared with norite. The limited seismic response was attributed to the blocky characteristics of the breccias where high stresses could shear through the natural discontinuities and cause a de-stress effect.

4 Bench scaling rule

During the preconditioning blasting trial period, the influence of bench scaling on seismic potential became apparent. Mine operators are trained to scale loose or hollow-sounding rock until the solid rock is reached because solid rock, without any damage, is easier to drill, bolt, and load explosives. However, when scaling loose, the buffer of damaged ground is removed along with portions of the preconditioning blasted area. This exposes the competent rock capable of withstanding high stress, consequently increasing the strainburst risk. Excessive scaling of the bench led to the formation of a bowl shape, which was consistent with the observations made during the sinking of the Creighton number 9 shaft (Redpath 1972). There were several cases where the operators removed up to 2 m of damaged rock (Figure 8a), thereby negating the effectiveness of the preconditioning blast. When over scaling occurred, there was a notable increase in seismicity along with an increased frequency of small slabs ejected from the bench. In addition to increasing strainburst risk, prolonged scaling activities of scraping and collecting thin stress-fractured rock was highly inefficient for advance rate compared with drill and blasting. As a result, a stop-scaling rule was enforced where operators would muck down to find any bootlegs but go no further regardless of how broken the ground was (Figure 8b). Operators used plastic collar pipes to keep the top of the blastholes open in severely broken areas.



(a)

(b)

Figure 8 (a) An image of a shaft bench over scaled by 1.5 m; (b) Image of a flat bench after stop-scaling was enforced

Once the stop-scaling rule was enforced, in combination with preconditioning blasting, there was a further reduction in seismic activity. Over the total preconditioning trial, the average number of seismic events occurring in preconditioning blasts was 66; however, if the blasts with and without the stop-scaling rule enforced were segregated, the average numbers of seismic events before and after the stop-scaling rule was enforced were 96 and 21 per blast, respectively. Figure 9 presents a comparison of the number of events and maximum moment magnitude of events during the trial period for preconditioning and non-preconditioning blasting.

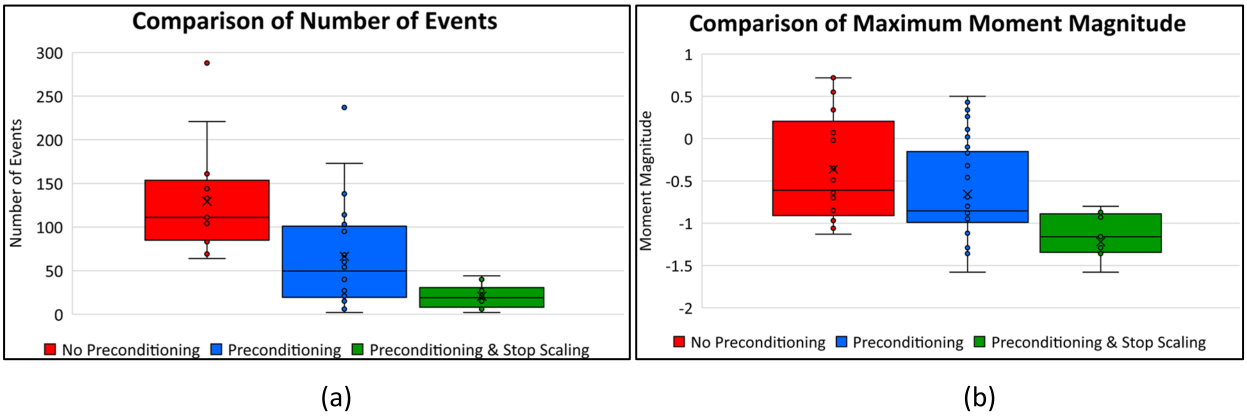


Figure 9 (a) Comparison of the number of events and (b) comparison of the maximum event size in the trial period for preconditioning and non-preconditioning blasting

5 Preconditioning blast strategy in gneiss

At 2,260 m the shaft sink crossed into a more competent and stronger gneiss. The average strength of the gneiss was 266 MPa; however, the gneiss has a wider range of strength ranging up to 400 MPa based on the lab testing completed. Although there was a notable increase in low magnitude seismic activity throughout the cycle as the shaft transitioned into gneiss, there was no significant spike in seismic activity as the bench was exposed. Due to the positive results of preconditioning blasting in norite and the transition lithologies, the strategy and design were maintained and continued to work well for the conditions that were encountered.

Although there was an increase in seismic activity in the gneiss, given the fact there was no rock ejection as the bench was exposed, a decision was made to trial removing preconditioning blasting from the overall blast design for one round at the 2,280 m level (20 m below the late granite breccia contact) to observe the seismic response. There was a consensus at the time that the preconditioning blasting was beneficial in reducing seismic activity as the bench was exposed; however, the extent of this benefit was not fully appreciated. The seismic event rate graph for the time frame when preconditioning blasting was removed in this level is presented in Figure 10.

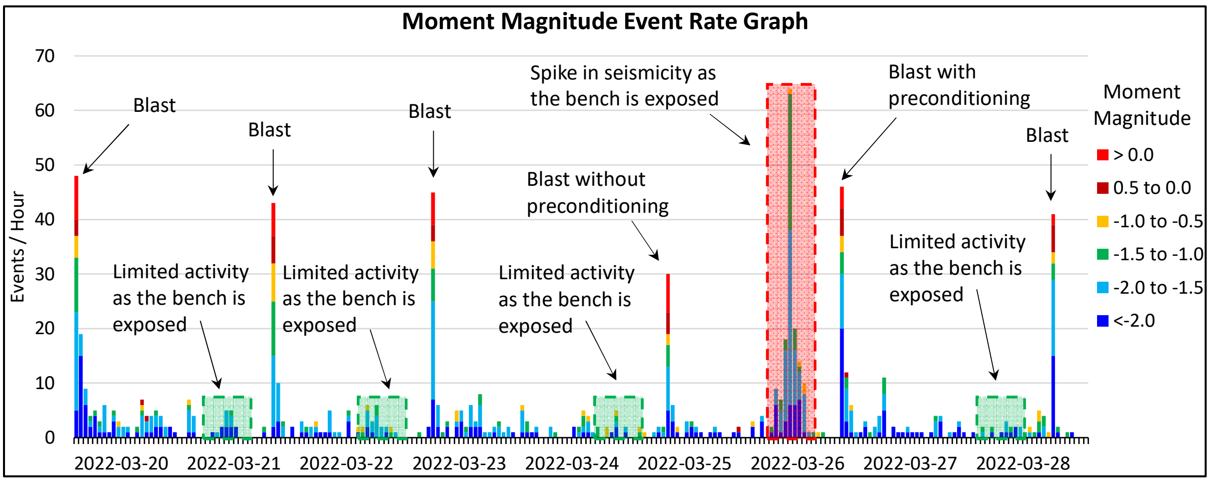


Figure 10 Seismic event rate graph showing several excavation rounds using preconditioning blasting and one without

The blasts utilising preconditioning before and after this non-preconditioned blast had a seismic event rate of 40–50 events in the first hour after blasting, while the non-preconditioned blast had an event rate of 30. This decrease in event rate was an indication that there was not as much energy released with the non-preconditioned blast compared with rounds that had been preconditioned. During initial mucking and bolting, there was nothing unusual reported from the operators or recorded on the seismic monitoring system. However, as the operators mucked closer to the bench and began to expose the solid rock, there was a significant increase in seismic activity (see the red time window in Figure 10). The operators reported bench spalling and ejection of small tensile slabs and shards up to 1 m off the bench, causing them to pull off the bench several times. As a result, preconditioning blasting was re-introduced on the following rounds, resulting in minimal seismic activity as the bench was exposed.

The preconditioning strategy continued with the eight-hole design until 2,342 m. In the final few rounds leading up to this elevation, the operators reported increased low-level seismic activity and ejection of small stress slabs and shards of rock up to 1 m off the bench. There was no clear difference noted in the seismic monitoring system or the televiewer logs in this area; however, it was evident that the rock strength in this area was elevated, rendering the preconditioning blast design used so far less effective. Figure 11 presents two images of strainbursting occurring on the bench at this elevation. There were many other events similar to that shown in Figure 11a, but the majority of these events were not picked up by the seismic monitoring system because they were so small (less than MW−2.0). The largest event has a moment magnitude of −1.3, which corresponded with the event shown in Figure 11b, which ejected 20 kg of broken rock approximately 10 m vertically.

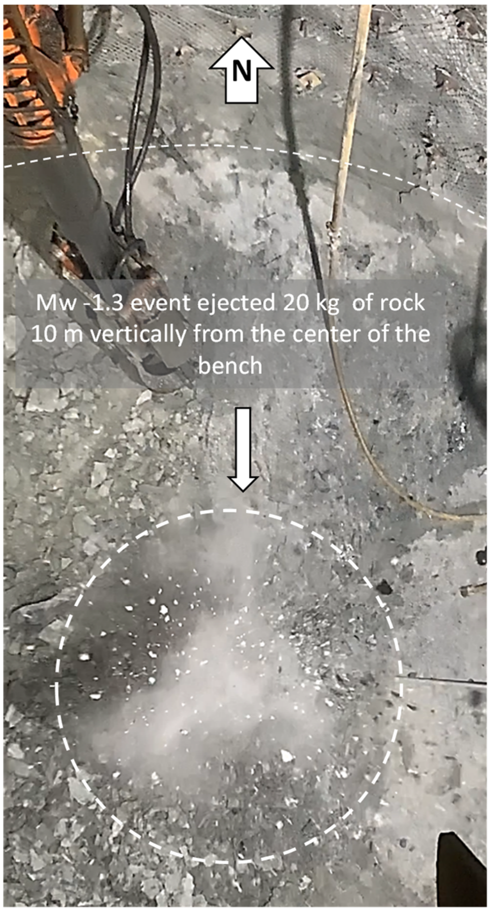


Figure 11 (a) Image showing a small strainburst on the bench with about 5 kg of material ejected; (b) Looking down from 10 m up at a strainburst ejecting about 20 kg of rocks from the bench

Due to the higher strength of the gneiss, there was less depth of failure occurring in the bench floor and walls, which resulted in high stresses flowing in closer proximity to the excavation than they were in norite. As a comparison, while drilling the bench in norite, the measured depth of failure in the middle of the round ranged from 0.5–1 m, while the depth of failure in gneiss on the bench was 0.05–0.4 m. For this reason, the preconditioning blastholes were reduced from 1.5–1 m past the planned round length to ensure there was a reduction in confinement around the preconditioning area. Figure 12 presents a comparison of stress concentrations in norite and gneiss, obtained from FLAC3D model simulation.

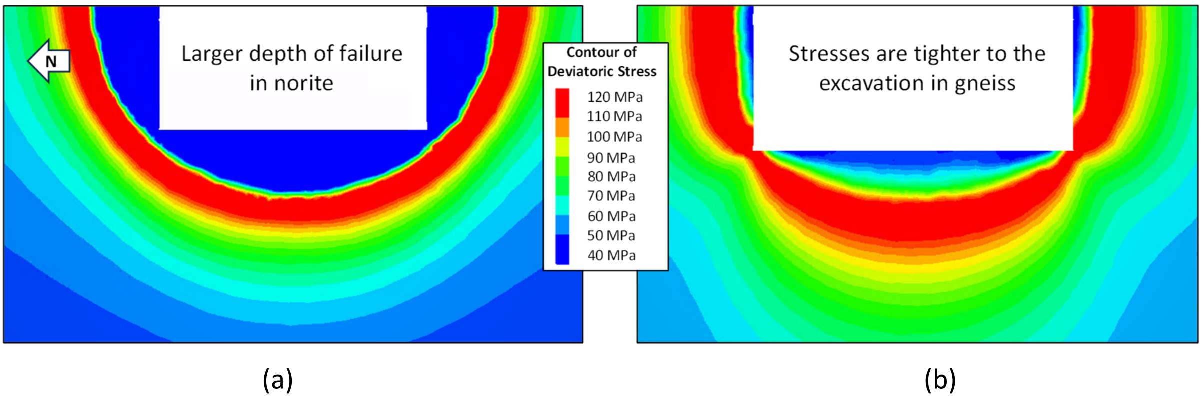


Figure 12 Shaft stress model simulation results showing the deviatoric stress distributions in (a) norite and (b) gneiss

Due to the strainbursting events in gneiss at the 2,342 m, the preconditioning blast design was modified to include a third cluster of four holes in the middle of the round with a 1.4 m spacing as shown in Figure 13a. The additional cluster of preconditioning holes was evaluated for two rounds. Although there was a reduction in seismic activity along the north, middle, and south portions of the bench, it was evident that the stresses had been shed to the northwest, northeast, southeast, and southwest corners of the bench where there was increased seismic activity, spalling, and small strainbursts occurring (yellow in Figure 13a). Based on the field observations and numerical models showing stresses flowing tight to the corners of the excavation, every other perimeter hole (red in Figure 13b) was lengthened by 1 m, loaded full column (4 m total) and blasted in the normal round sequence. The three clusters of four preconditioning holes were detonated first in the sequence. The preconditioning blast strategy presented in Figure 13b has 6.3% of the total explosive in each 3 m long round dedicated to preconditioning.

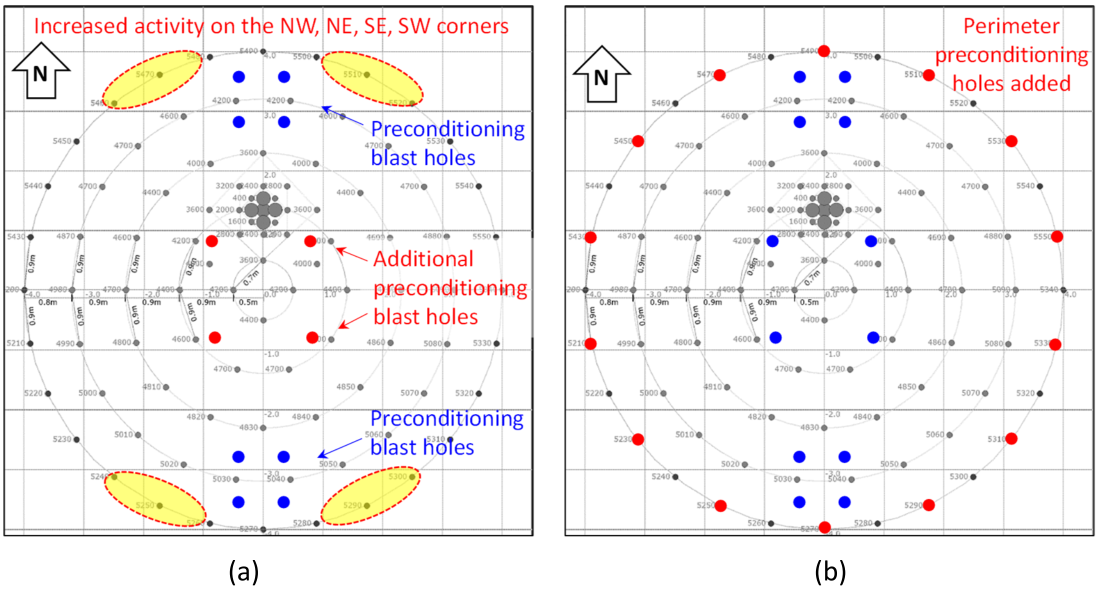
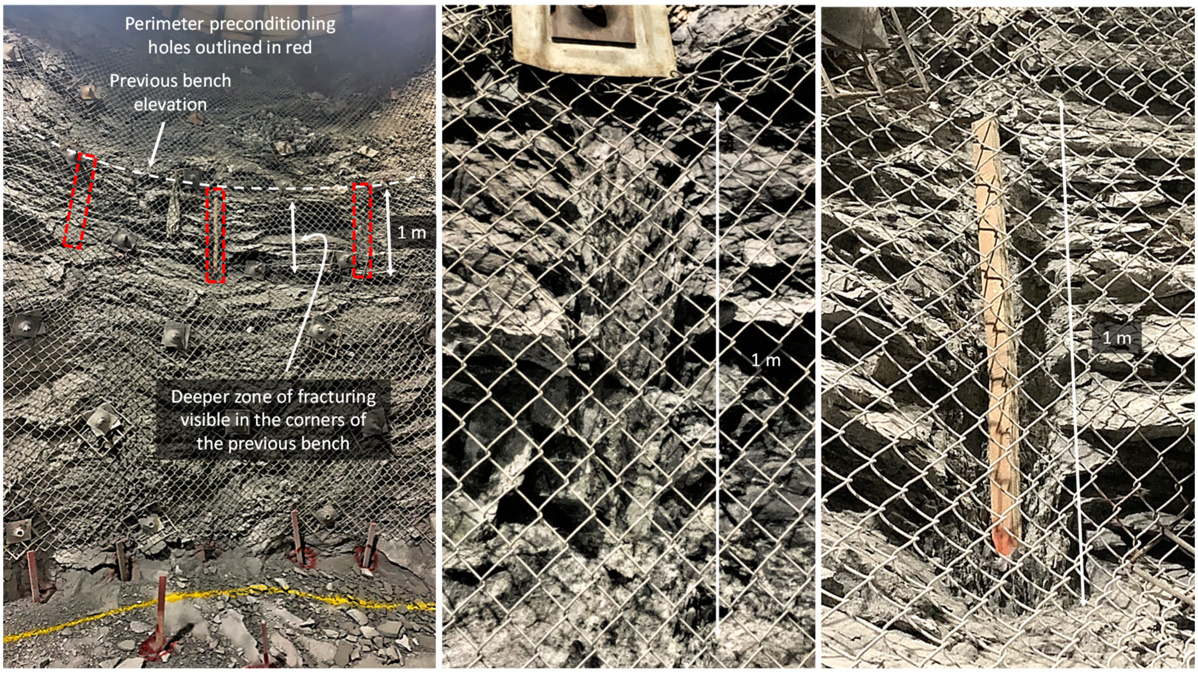


Figure 13 (a) Plan view of the blast pattern with the centre cluster of holes added showing the resulting locations of increased seismic activity (yellow circles) and (b) plan view of the modified blast pattern for shaft sinking in gneiss in the remaining segment

There was an immediate improvement in the rock mass response when the perimeter holes were lengthened with no spalling or bursting recorded. Figure 14 shows an example of the perimeter preconditioning holes exposed in the wall of the shaft. The depth of fracturing was increased in the corners of the bench when the perimeter holes were lengthened indicating the preconditioning efforts were successful in disrupting the flow of high stresses and pushing the stresses deeper into the rock mass. This preconditioning strategy and design was used for the remainder of the shaft sink to 2,635 m depth, which was entirely in gneiss.



(a) (b)

Figure 14 (a) Image showing an increase in the depth of failure in the North wall below the previous bench when the perimeter hole length was increased; (b) Examples of the fracturing observed around the lengthened perimeter holes

Figure 15 presents the relation between depth and the cumulative apparent volume (CAV) recorded by the microseismic monitoring system during the blind sink. CAV, measured in cubic metres, is a measure of co-seismic deformation(Mendecki et al. 1999). A steep slope in the graph shows low seismic response, and a flat slope corresponds with high energy release. The data exclude all lateral development at the shaft stations so that only the activities associated with the vertical development are examined.

As the sinking approached and passed through the Red Clay Fault at 2,475 m, seismic activity was relatively low, which also coincided with the rock mass becoming increasingly blocky. However, about 5 m below the Red Clay Fault, both the seismic event rate and the average seismic magnitude increased rapidly. This coincided with the rock mass becoming more homogeneous. The operators also reported increased wear in drill bits, indicating stronger rock in this area. It was concluded that the fault altered the field stress such that the field stress below the fault is much higher than that above the fault.

For the entire blind sink (720 m), over 40% of the CAV recorded was between 2,480 and 2,530 m (50 m). While sinking through this area, there were 31 seismic events greater than MW0.0 and two were greater than MW1.0. These events occurred randomly throughout the development cycle, rather than solely when the bench was exposed, and they mainly occurred in the lower walls. Preconditioning blasting continued through this section of the shaft. Although there was no ejection of rock from the bench, preconditioning blasting appeared to be less effective in preventing the large events from occurring or making the events occur with the blast when operators were not present. Ultimately, operator access to the bench was eliminated in this area with all work performed from a deck that was lowered from the Galloway. This remote work was highly inefficient with advance rates slowing from 2 m/day to 0.7 m/day through this section.

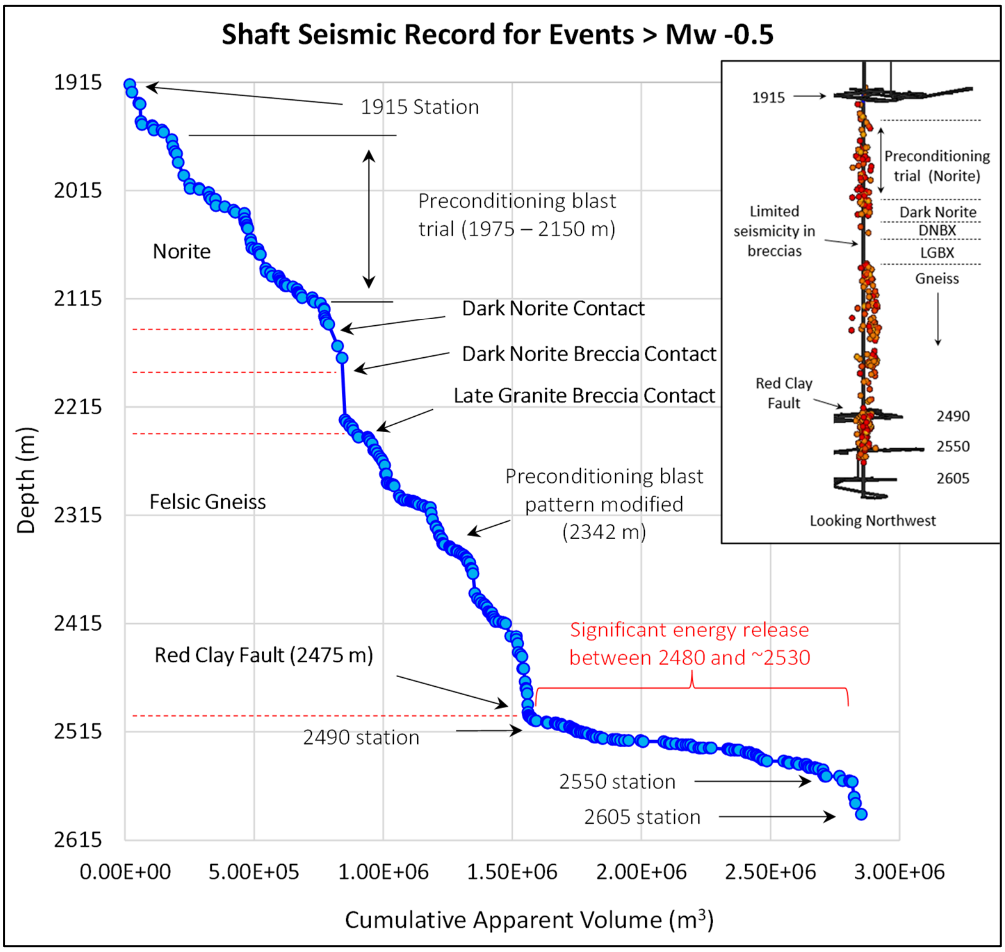


Figure 15 Distribution of the cumulative apparent volume along the depth for the blind sink segment with a snapshot of the seismicity recorded by the seismic system in the top right (events > MW−0.5)

6 Conclusion

This study detailed the development and evolution of a preconditioning blast design and strategy used while completing the blind sink portion of the Onaping Depth internal shaft from 1,915–2,635 m. Before starting the shaft sink, a dense seismic array was installed and used to monitor the rock mass response. Based on seismic monitoring, it was found that there was a fundamental difference in the timing of seismic energy release in a shaft sink compared with lateral development. As opposed to most of the seismic activity occurring immediately after a blast in a lateral development round, a shaft round has a limited ability to redistribute stresses until mucking begins due to the blasted muck providing confinement to the walls and floor. Therefore, the bulk of activity does not occur until the bench floor is exposed, which is when operators are present, resulting in a higher risk profile.

A review of preconditioning blast strategies in literature found limited basis for the designs used in shaft sinking operations and a lack of quantifiable evidence to support the benefits or success of preconditioning blasting. Furthermore, there is no established methodology to design a preconditioning blast for an individual mine site with specific rock mass characteristics or stress conditions. An initial preconditioning blast pattern was developed while sinking through norite based on the observations made in the field. A key parameter was the depth of failure below the excavation. Areas of the bench that had less than 0.3 m of stress-fractured rock, had increased risk of strainbursting. The observations were used to calibrate the numerical models, which helped to design the preconditioning blast. Implementation of the preconditioning blast had immediate positive effects that greatly improved operator safety by significantly reducing the amount of seismicity as the bench floor was exposed. Another important experience is that it is imperative to limit the operators from over scaling the bench as this would negate the effectiveness of the preconditioning blast.

As the shaft sink transitioned to the stronger gneiss rock unit, conditions on the bench deteriorated with active spalling and strainbursting occurring. Based on field observations and numerical modelling, it was found that the high stresses were flowing closer to the excavation, rendering the initial preconditioning design less effective. Additional preconditioning holes were added to the pattern and the existing preconditioning holes were repositioned to better disrupt the flow of high stresses and push the stresses further away from the excavation. These changes significantly reduced seismicity, spalling, and strainbursting occurring on the bench, thereby improving operator safety.

As seen in this work, it is highly unlikely that one preconditioning blast design will be successful across multiple mine sites or for that matter, across various lithologies at one specific mine site. The preconditioning blast must be tailored to the specific conditions encountered. As a preconditioning blast design is implemented, a constant feedback loop must be established to monitor changes in the rock mass conditions and determine if changes to the pattern are required. Finally, a quantitative method of assessing the performance of the preconditioning blast must be established with a microseismic system and field observations. Only in this fashion can shaft sinking in deep and burst-prone ground be conducted safely and efficiently.

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