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Effective ground support system design to manage seismic hazard in a high stress diminishing pillar at a Vale mine

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Abstract

Mining of the Copper Cliff Mine, 810 Orebody between 3350 and 3540 Levels became increasingly challenging and prone to rockbursting as the zone was diminished and the total extraction approached +90%. The receding sill pillar was highly stressed and mining in the area was further aggravated by the presence of an aplite dyke. The mining area had completed production on all sides and the sill pillar measured 9 to 15 m thick above the extraction horizon. With the final mining stages, each stope experienced higher and higher stresses due to the decrease in the sill pillar strike length. A large rockburst caused production to be suspended while extensive rehabilitation efforts were put in place. This resulted in delays to production of more than six months. Despite the extensive reconditioning with shotcrete arches and the use of destress holes to fracture the ground to break-up the stress regime, the mining of the remaining stopes continued to result in magnitude events. Several events, as large as 2.6 Mn, were recorded with each successive panel, further compromising the stability of the access drifts and ground support.

To be able to successfully extract the remaining resources, ground support design was a key component in the safe production planning. Up until this point, the ground support focus had been an increasingly stiff support system. Operators consistently complained about increased difficulty with installation of ground support products, especially where resin was required. The installation of shotcrete arches, while relatively simple to install, were initially effective in prevention of major top sill failure. Yet, with subsequent mining, the seismicity caused fracturing/buckling of the shotcrete arches due to its brittle nature. The restricted movement of the rock mass thereby resulted in breakage of the arches and shotcrete, compromising the integrity of the support system.

A new strategy was created for recovery of the ore in this area of the mine. This paper describes the design process of a yielding support system. The support system was regularly monitored using Detect™ cable bolts and multi point borehole extensometers in top sill and bottom sill locations. Compared to the initial challenges in mining the area, the implementation of the yielding support system and re-entry procedures allowed for the safe production with improved productivity and reduced rehabilitation requirements. The paper also describes the ground conditions, geotechnical design, and monitoring of the support during the course of extraction of the remaining panels. Instrumentation results substantiate the effectiveness of the support design, the ground response following major seismic events and behaviour of the new ground control system, confirming three dimensional numerical modelling conclusions.

1 Location

Vale's Copper Cliff Mine is located on the southern edge of the town of Copper Cliff, situated in the City of Greater Sudbury in Ontario, Canada. The mine comprises the south-side and north-side ore zones and infrastructure, previously mined as Copper Cliff South Mine and Copper Cliff North Mine. These mining zones have been in operation for more than 40 years with initial production from open pit operations. Later, underground mining was established using ramp access and vertical shafts. Recent production on the south side was from several fronts including the 810, 850, 865 and 880 orebodies. With reduced nickel demand in 2008, the south side zones are on a suspension of operations status.

2 Regional geology

Sudbury Igneous Complex is an elliptical region of a series of igneous formations. Copper Cliff Mine lies on the southern range of the Sudbury Igneous Complex, its orebodies located on the Copper Cliff Offset (refer to Figure 1). The Copper Cliff Offset is composed primarily of Quartz Diorite. Within the mine environment, the offset crosscuts Huronian Metasediments and Metavolcanics. In turn, the offset is cut by narrow Aplite, west trending Quartz Diabase (Trap), and northwest trending Olivine Diabase Dykes. Near the contact with country rocks, the Quartz Diorite has been contaminated with Sudbury Breccia adjacent to the dykes. Fragments of Metasediment, Metavolcanics, Amphibolites and Gabbros of 12.5 mm to over 3 m wide are contained in a fine-grained metamorphic textured matrix. Mineralization occurred in Quartz Diorite and major Sulphides include Pyrrhotite, Pentlandite and Chalcopyrite with mineralogy consistent with other mines of the Sudbury District. Adjacent to Quartz Diorite, Chalcopyrite enriched sulphide stringers have been formed. Typically Chalcopyrite content increases to the extremities along strike and down-dip. The locations of the economic ore zones are generally along the east (hangingwall) contact, but may be in the centre or along the west (footwall) contact of the Quartz Diorite dyke. The offset and the country rocks have been folded about a north-easterly trending axis. Folds are open and have steeply dipping axial planes, many crosscutting dykes were injected later.

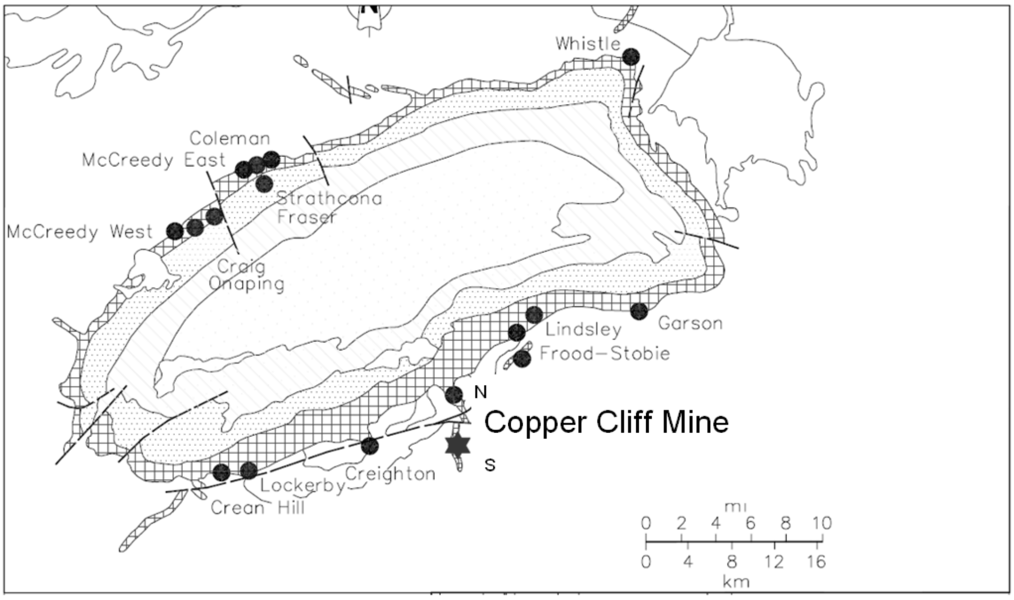

Figure 1 Geology map of the Sudbury Basin

3 Local geology of 810 Orebody

Mineralization of the 810 Orebody extends from surface to 5000 (1524 m) Level, where it is remains open at depth. The Evans Fault offsets the ore between 320 (97 m) and 500 (152 m) Level. Folding has overturned the ore zone near the 1500 Level (1524 m horizon). The ore hangingwall contact dips 60 degrees to the east to 2430 (740 m) Level, beyond that steepening to 72 degrees.

Ore types consist of disseminated blebs of sulphide in Quartz Diorite (DSQD) and inclusion massive sulphide (INMS). The ore zone varies from 1.5 to over 30 m wide. High precious metal values have been outlined in the Quartz Diorite Dyke between 3000 (914 m) and 4500 (1372 m) Levels. Hangingwall metasediments are blocky due to intersecting joints. At lower elevations the hangingwall is locally weakly sheared.

This orebody is distinct from the other orebodies as thin aplite dykes transverse the ore zone (refer to Figure 2). These aplite dykes are very stiff and are known to result in violent failure of the rock mass with increases in induced stress levels. The 810 Orebody has a strike length of a few hundred meters, varying slightly level to level.

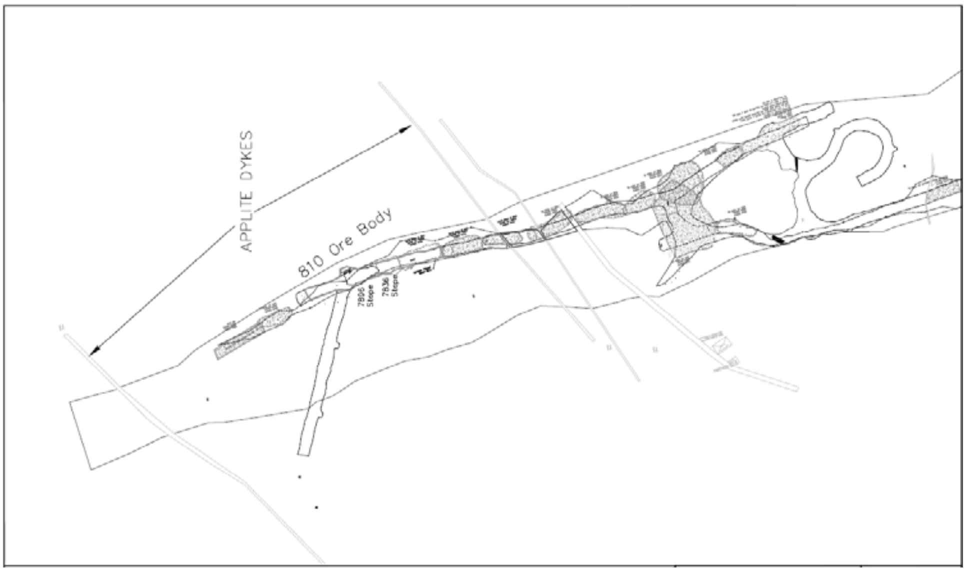

Figure 2 Local Geology of 810 Orebody at 3350L

4 Orebody extraction

Underground mining first employed shrinkage stoping and cut and fill methods in the upper levels. Later, Vertical Retreat Mining and variations of a slot-and-slash method were used for production in the lower levels. The orebody has been completely mined out above 3320 (1000 m) Level horizon, with the exception of fifteen meter crown (sill) pillars at the 2700 (825 m) to 2750 (840 m) and 3000 (915 m) to 3050 (930 m) Levels.

Subsequent mine design established a bottom up mining plan from 3930 (1130 m) to 3320 (1012 m). Three mining horizons were established which included 3930, 3700 and 3540 (1080 m) Levels. With the lower horizons completed, extraction of the final horizon, 3540 to 3320 Level remained in place. The majority of a crown pillar, 3350 to 3320, remains unmined.

Increased difficulty with extraction of the resource at the final horizon was complicated by the fact that a diminishing pillar had been created as a result of a centre-out mining retreat towards a stope previously mined from 3320 Level. The latter stope had been mined earlier as an opportunity to dispose of development waste rock. Later, as mining approached the location, rock was removed and the stope was refilled with cemented hydraulic mine tailings.

The pillar is completely surrounded by filled stopes and an aplite dyke runs through the production area. The light-coloured, fine-grained granitic rock consisting mainly of quartz is very stiff, brittle in nature and prone to violent failure including rock ejection due to rockbursting.

The influence of this dyke could be occasionally seen in the microseismic data. During extraction of stopes in the vicinity, it was apparent that the stiff dyke was a mechanism for re-distribution of stress along it into the hangingwall. Always occurring following strainbursting at an open panel, the majority of these events were found to be of a larger magnitude than the local strain events themselves (refer to Figures 3 and 4). This was particularly true with earlier stopes mined in the pillar, notably 7716 and 7776 Panels.

Furthermore, a thin, high-stress crown pillar varying from 9 to 15 m in thickness remained in place following extraction of the panels. The crown was diminished as each stope was extracted, resulting in high stress levels and uncertain behaviour of the pillar. Early in the centre-out sequence, a major rockburst resulted in suspension of mining activities for several months for extensive rehabilitation of the area.

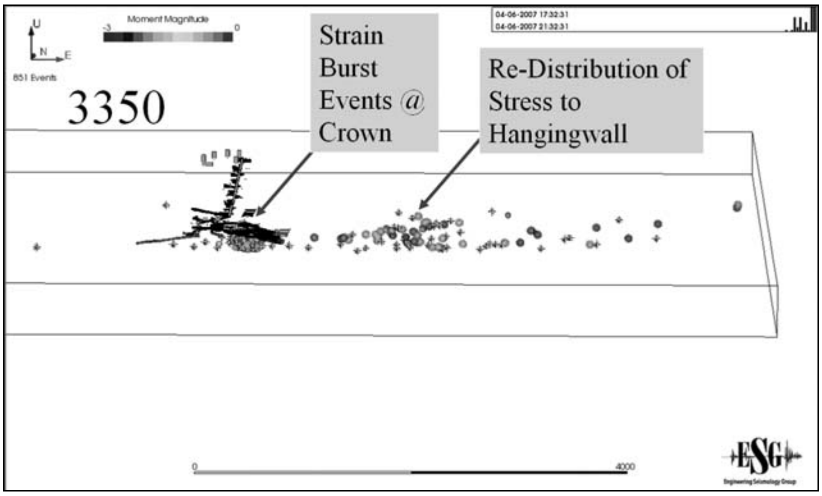

Figure 3 April 6, 2007 seismic activity following 3350–3540 Level, crown blast

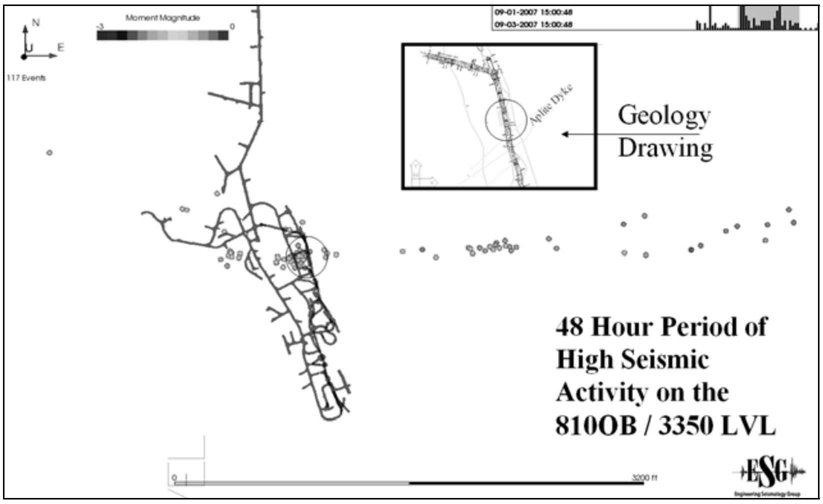

Figure 4 Sept. 1–3, 2007 seismicity during 3350–3540 Panel 7776 mining (not directly blast related)

5 Rehabilitation of excavations

Reconditioning of the crown pillar included installation of shotcrete arches as a protection against additional damage to the crown pillar above the extraction horizon as experienced with the rockburst in the topsill. An attempt to break up the rock and divert stresses was made by drilling a tight pattern of closely spaced, un-blasted destress holes. No conclusive evidence was ever found to support that this effort was successful. The ground at the holes did break up near the topsill, but became problematic in drilling of subsequent blast-holes and many re-drills were required during the life of each panel. It was the opinion of many that the holes were more of a hindrance than a benefit. During drilling of two stopes ahead of the mining front in the footwall, an interesting observation was made. Drill water leakage could be seen in the distant 15 cm boreholes, approximately nine to twelve meters deep, as far as fifteen meters away from the drill location at the panel area. Closer observation revealed that the water was channelled along the aplite dyke, as observed by the light texture of the granules in the water.

Despite the measures taken, each stope continued to result in seismic events with magnitudes as large as 2.6 Mn. Recommendations were made October 1, 2007 to abandon the destress drilling program in favour of an enhanced 'yield-over-stiff' support system designed to protect against strainburst activity for anticipated magnitude levels. Reconditioning commenced in November 2007 and was completed by the end of January 2008. In total, 63 m of rehabilitation was completed throughout the 3350 Level instrumented area as well as 37 m at the 3540 Level bottomsill.

6 Geotechnical design

To enable successful extraction of the remaining resources, ground support design was used to formulate a safe production plan in the receding pillar area. Up until this point, the focus had been on installation of an increasingly stiff support system. The original support system included mesh screen installed with a mechanical/rebar mix. This system worked well to enable crews to continue development in the primary stage, but years later, due to increased convergence as a result of mining, the bolting crews faced increasing difficulty with subsequent installations of the support system. Installation of shotcrete arches, while less problematic to install than the rebar bolts, were initially effective in prevention of damage. However, due to the brittle nature of this support and the restricted movement of the rock mass, large seismic events resulted in cracking of shotcrete and breakage of the arches during production. This then compromised the integrity of the overall support system.

A new strategy was created to arrest the ground support deterioration in the area. Brittle failure of shotcrete and breakage of arches warranted use of a yielding support system. With a very stiff system already in place, an effective yielding support system component would accommodate bulking of the rockmass while helping to preserve the integrity of previously installed support.

Experience with yielding support systems (Punkkinen et al., 2007) in use for deep mining at Vale's Creighton Mine was brought to the mine and communicated with the highly qualified, experienced crews. They were very responsive to the new ideas as was indicated from the results of a short workshop with the workers. The schedule called for rehabilitation of the bottomsill or 7786 Stope as well as repairs to shotcrete arches on the topsill. A support system consisting of 46 mm diameter friction sets (fs46™) securing #4 gauge mesh was chosen for its capability to accommodate large deformations from bulking of the rock mass and relative ease of installation. This system was installed following repairs to the cracked shotcrete using an application of steel fibre product. In combination with the initial stiff primary support system already in place, the effective 'yielding-over-stiff' system design greatly enhanced ground support effectiveness, guarding against violent failure of the excavation due to mining related, and strainburst seismic activity. Just prior to mining, intersections on the bottomsill horizon were cable bolted with 4.9 m, double twin/bulge plated cable bolts to ensure additional protection against deep seated wedge failure beyond the depth of primary ground support. Procedural items, including a site specific procedure which included pull testing of the large diameter friction set bolts in the bottomsill, was carried out as part of a quality control check on the process. Care was taken as to not skew results by pulling through holes drilled into shotcrete. Capacity of the 2 m length test bolts was between 8 and 9.5 t (refer to Figure 5). When deemed successful, proven superior to the current methodology in place and recommended for future use, the Site Specific Procedure would then be followed by a complete Vale Management of Change (MOC).

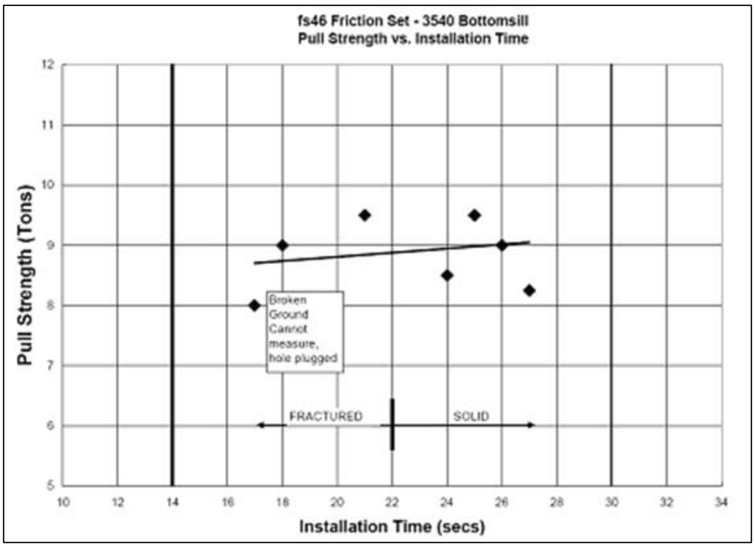

Figure 5 Pull testing results of FS-46 bolts

7 Numerical modelling

For this case study, Map3D®, a comprehensive three-dimensional computer program based on the boundary element method, was used to develop a better understanding of the stresses in the thin crown pillar and diminishing pillar (refer to Figure 6). As the program is a linear elastic model, it is understood that post-peak failed zones may not be properly depicted. Modelling results were calibrated by instrumentation data from the instrumented cable bolts, the multi-point extensometers, as well as the ESG microseismic array already in place around the excavation.

A deviatoric stress limit of 70% of the uniaxial compressive strength was used to indicate failure. An UCS value for the ore averages approximately 115 MPa, with surrounding Metasediments at 140 MPa. Stiff aplite dyke material can vary from 200–240 MPa and is most likely to burst violently when loaded to failure. Zones of high deviatoric stress, low confinement with large displacement can be identified as failed zones (refer to Figure 8 showing stresses prior to the extraction of 7896 Stope). For the ore zone, the failure zone is inferred at 80 MPa. Behaviour of the support was visually observed where large displacements were recorded by the instrumentation.

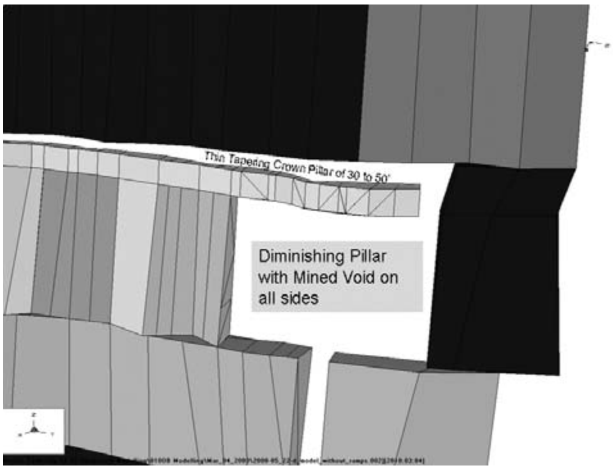

Figure 6 Numerical model showing long section of mining and tapering crown pillar

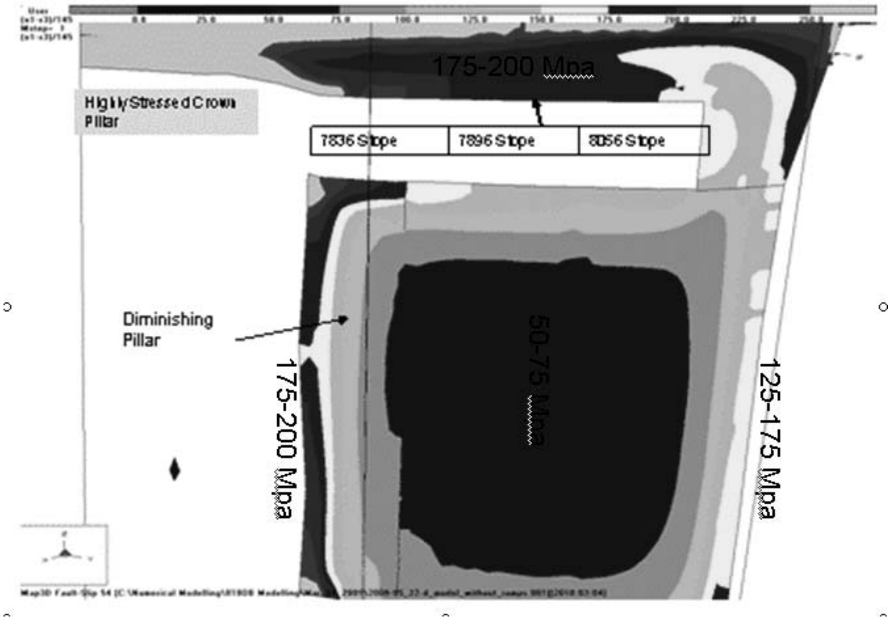

Figure 7 Deviatoric stresses (σ_1–σ_3) at diminishing pillar and crown pillar

8 Support effectiveness and monitoring

Performance of the support system was monitored using yield-point DETECT® cables and multi point borehole extensometers (MPBX). The principle of operation of a DETECT cable is based on a miniature inductive load meter small enough to be recessed into a surrogate tubular king wire in the centre of the seven wire cable. The inductive load meter is a miniature inductive displacement sensor comprising a precision coil. During loading, stretch of the king wire tube results in displacement of the precision coil relative to its high permeability core. The corresponding change in coil inductance causes a variation in the frequency of a resonant electrical circuit which is measured by the microcontroller in the instrument head. The accuracy of the displacement sensor is enhanced by an empirically derived temperature compensation algorithm that is applied by the microcontroller. Measured displacement is calibrated to the applied load (Hyett, A.J., 2010). DETECT instrumentation was chosen due to the direct read-out capability of the manual interrogation unit. This instrumentation package would become part of the re-entry procedure used in this area.

Two stopes (7836 and 7896) were extracted following the installation of the new support system and instrumentation (refer to Figures 8–10). All locations had a single DETECT MPBX and cable installed within one meter of each other to accurately measure and compare load versus displacement. Node/anchor locations were set up at 1.2, 2.4 and 3.6 m intervals for 3.6 m cables (3350 Level) and at 1.2, 2.7, 4.3 and 6.1 m for 6.1 m cables on 3540 Level. All instrumentation was recessed 0.5 m up into the borehole (+0.5 m to physical anchor locations). One DETECT cable on 3350 Level was destroyed from the onset, its twin, #65 (a 6.1 m, multi point borehole extensometer) could only be installed 4.4 m into a drill hole, three load meters remained operational inside the hole.

Seismic events continued as the pillar recessed with the advancing mining front. Extraction of two stopes, 7836 and 7896, advanced the mining front to a single panel while 8036 Panel remains unmined to date. For logistical purposes, the 7836 Panel dimension was enlarged with a blast-hole slash to accommodate muck removal at the bottomsill. Instrumentation in place provided a perfect opportunity to observe the support system's ability to withstand possible dynamic forces in the area.

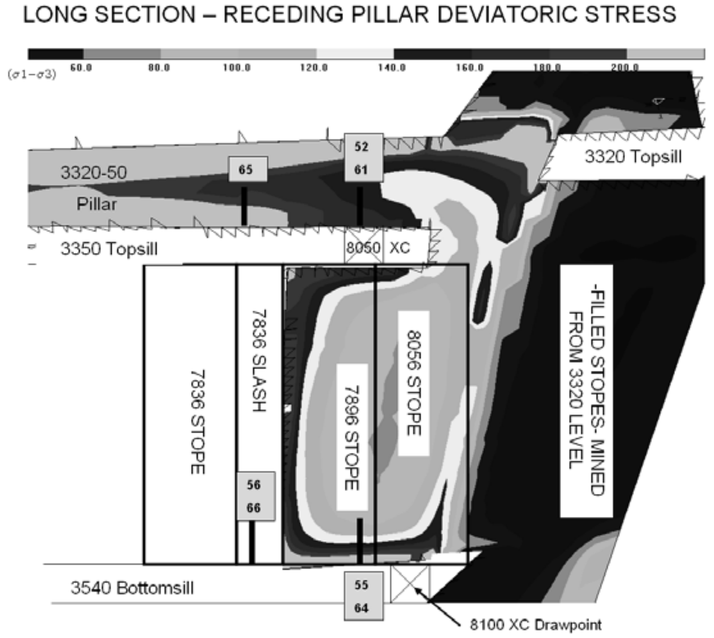

Figure 8 Monitoring locations and deviatoric stress level (σ_1–σ_3) at the final mining step

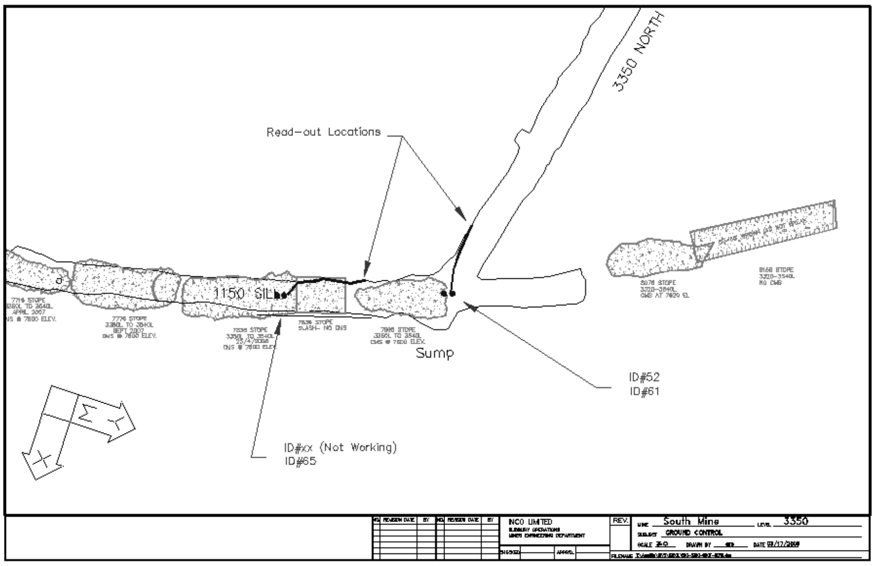

Figure 9 3350 topsill monitoring locations

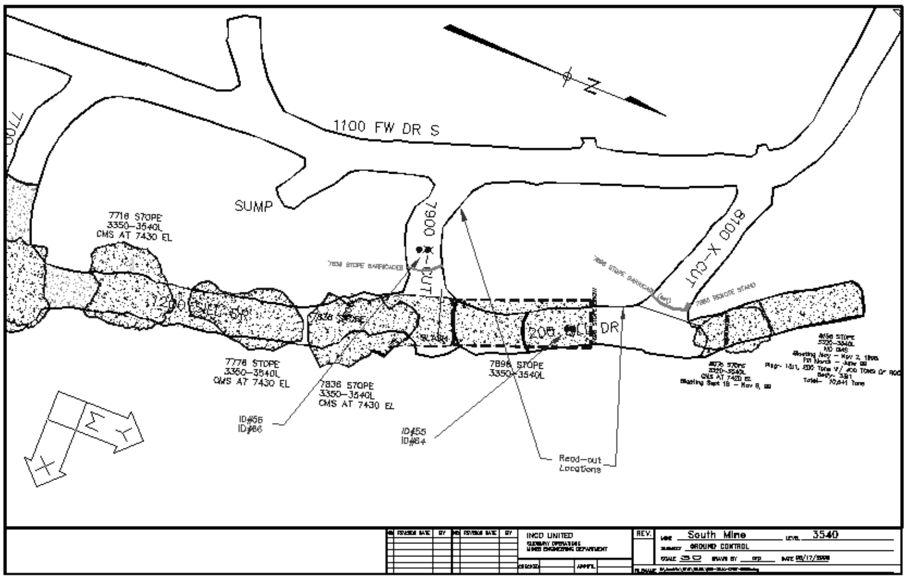

Figure 10 3540 bottomsill monitoring locations

9 Monitoring Program

The monitoring program included a site specific re-entry procedure which was followed after each production blast. Affected areas were pro-actively restricted for a minimum of two hours after each blast by the supervisor. Trained in its use, the supervisor would then check the ESG SeisVis© 'Shifter's' Visualizer at the Refuge Station to ensure that seismicity was at an acceptable background level. If seismic activity did not reach an acceptable background level after the waiting period, the area would remain restricted. Technical assistance was available from ground control on-call personnel. Based on the above information, the supervisor would then complete a visual inspection of all restricted areas ensuring that there was no damage to ground support or excavation. As part of the protocol, at the top and bottomsill locations of each set-up, instrumentation readings were recorded with a hand-held Yield Point data logger by the supervisor prior to re-opening the area to ensure excessive displacement and loading of ground support had not occurred. Data was submitted to ground control each shift recorded. Results obtained with the installed instrumentation at the individual stations on 3350 and 3450 Levels are displayed as temporal plots in Figures 11–14.

3350 Level: Figure 11

At the south end of the monitoring area, only the displacement reading was available. Load readings were unavailable due to a pinched cable. When the 7836 crown blast undercut the instrumented pillar above the topsill, total displacement increased to 10mm. The 'slash' increased the reading to 18mm which increased to 26 mm while undercut prior to the fill cycle. Mining of the 7896 further increased displacement to 33 mm, no reading was available after the 7896 crown due to restricted access to the readout location. Note that only three of the cables four load meters were physically installed in the 4.5 m hole (1.2, 2.7 and 4.3 m).

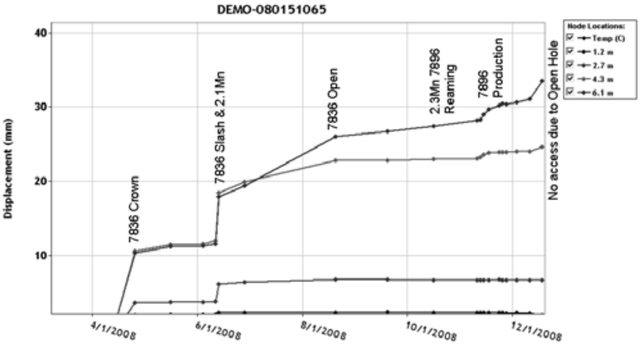

Figure 11 MPBX #65 3350 topsill

3350 Level: Figure 12

At the north end of 3350 Level, even when undercut by mining of the 7896 panel, less than ½ ton of load is observed. This corresponds to a gradual accumulation to 7mm with mining activity until the MPBX was damaged. Little change in load/displacement results were observed throughout the mining cycle at this location.

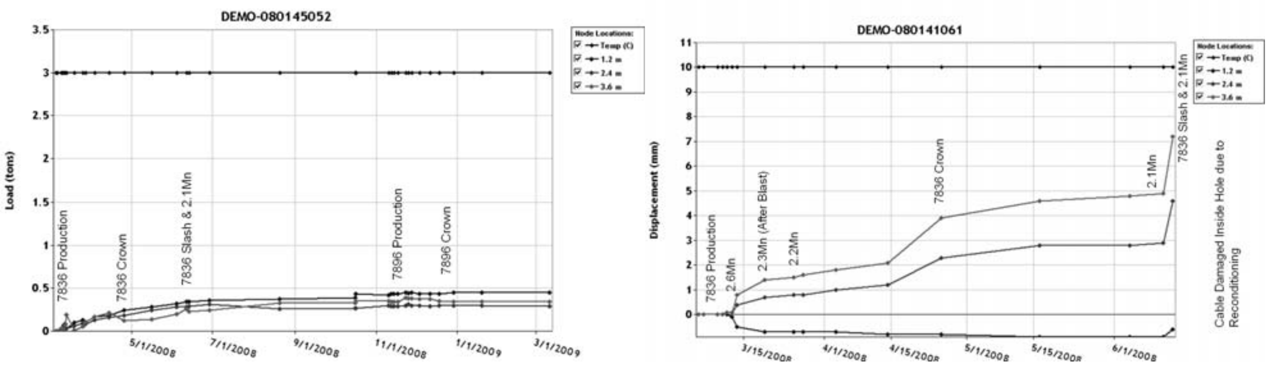

Figure 12 Detect Cable #52 & MPBX #61 3350 topsill

3540 Level: Figure 13

Located at the south end of the monitoring area, these instruments were installed slightly to the footwall of the ore zone. No tangible increases in load (~ ¼ ton) were recorded until after the seventh blast and a 2.3 Mn event which followed. As mining of the 7836 panel continued, the bulk of total displacement progressively increased to 4 tons after the crown was blasted and to 5 ½ tons after the 7836 slash. The gradual increase to displacement corresponds with changes in load as the mining front approached. A total displacement of approximately 5 mm was measured, little load or displacement was observed after the mining front passed the instrumentation location.

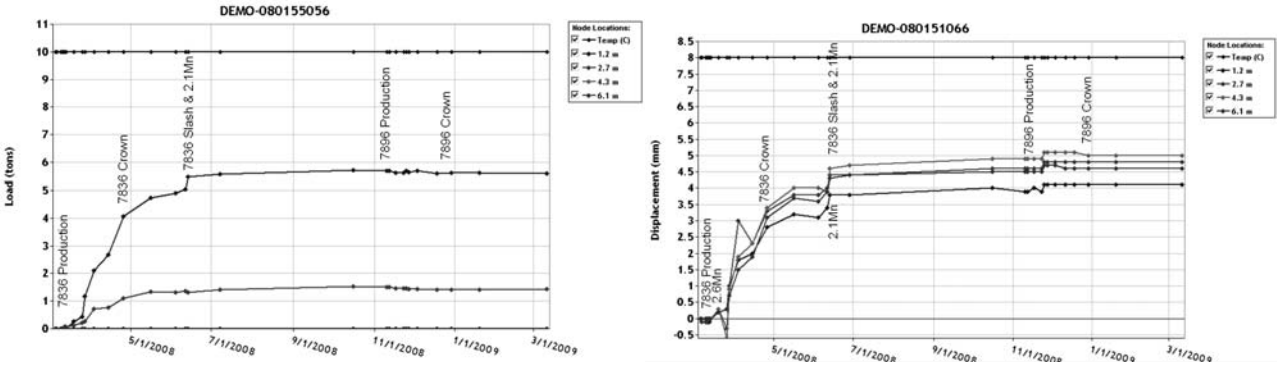

Figure 13 Detect cable #56 & MPBX #66 3540 bottomsill

3540 Level: Figure 14

Approximately ½ ton of load was measured along the north end cable until the seventh blast, after which a subsequent 2.3 Mn event destroyed the instrumented cable bolt. The read-out confirms that the bolt broke between the 1.2 and 2.7 m point due to dynamic loading as a result of the local event. Prior to this, minimal displacement (approx. 1½ mm) had been observed, after which an increase to 16 mm coincided with the seismic event. As mining progressed, a linear increase to 20 mm occurred with the several blasts leading up to the slash, increasing to 30 mm following it. By the time reaming had been completed in the 7896 Stope raisebore slot, increases to 37 mm were apparent. When 7896 production physically approached the MPBX location in November 2008, displacements reached the full limit capacity of the instrumentation (>94 mm).

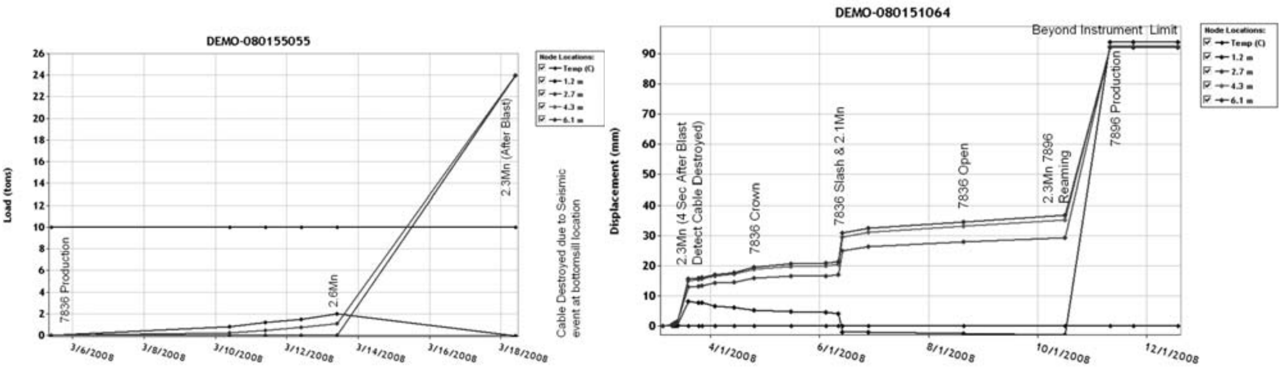

Figure 14 Detect cable #55 & MPBX #64 3540 bottomsill

10 Field observations

An event registering a magnitude of 2.6 Mn occurred 13 March 2008 resulting in damage in the 3350 topsill area (refer to Figure 15 'topsill location'). The proper protocols and investigations were completed following this event. Most damage was observed in the walls of the topsill access drift. For a distance of approximately 40 m, shotcrete was observed as having peeled from both walls and cracked along the back, with increasing intensity to the sill drift intersection. This event resulted in damage to both mechanical as well as friction bolts at intermittent locations. The topsill had been reconditioned November 2007 to February 2008 with secondary support in the form of #4ga mesh installed with 2 m length, (fs46™) friction set bolts installed over arches and shotcrete and remained in good shape. The source location of the seismic event plotted within the stope. The stiff arch and enhanced yielding ground support system combination performed well.

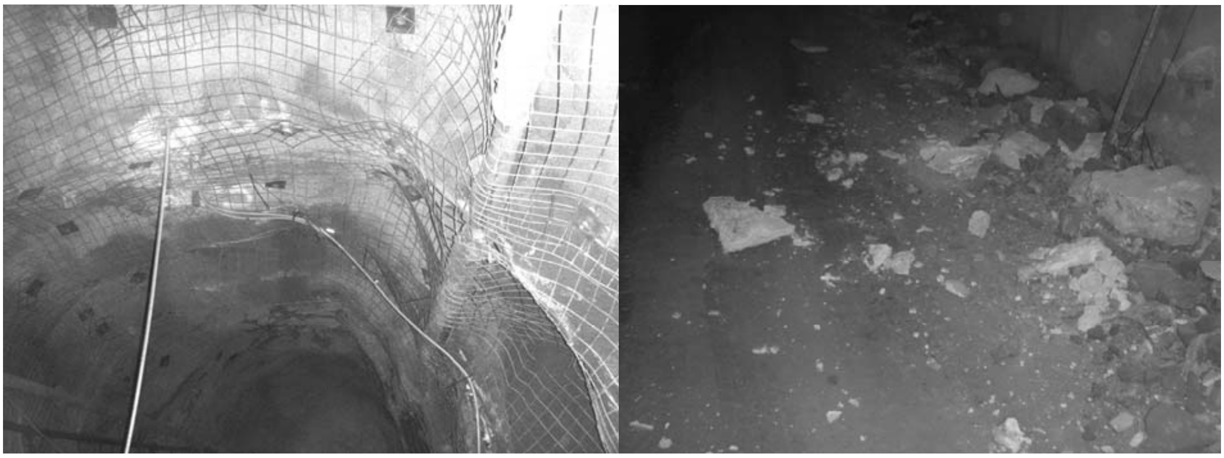

Figure 15 Back and floor of 7836 bottom and topsill following the March 13, 2008, 2.6 Mn event

The seventh production blast was fired on March 19, 2008 at 19:05 hours. An event, measuring 1.8 Mn and occurring seven seconds after the blast occurred within the panel boundary. Four minutes later, an event felt on surface registering 2.3 Mn plotted in the bottomsill. This area was restricted for the afternoon shift and re-opened the following dayshift following a ground control review of seismicity and inspection of the workplace. Some additional shotcrete cracks were observed at unscreened shotcrete arch locations at the topsill area, minor cracking of shotcrete was observed beneath mesh at the bottomsill.

The first blast in the next panel, Panel 7986 was fired November 10, 2008, bringing bottomsill MPBX #64 within two meters of the newly established stope brow. Displacement readings maxed out the instrumentation to 94 mm at each load meter position (refer to Figure 14).

On December 16 at the end of dayshift, Panel 7986 was brought up to the final break-through position. Due to the high stress regime in this area, the site-specific protocol restricted access to nearby areas for a minimum of two hour duration prior to re-entry. In this case, a subsequent review revealed a high level of microseismicity and the re-entry time was extended. Approximately three hours later, a 2.6 Mn event occurred at the bottomsill location. The area remained restricted until seismic clearing in the morning established safe re-entry for a full ground control/operating inspection of the affected areas.

The event resulted in a rockburst which destroyed MPBX #64 with displacement at the brow and wall corner at the bottomsill. By this point, the original arch-shaped bottomsill drift contour as shown in Figure 15 had extensively deformed (refer to Figure 16). Ground conditions were at a point that it was decided that the remaining ore in the stope was to be mucked out remotely from a safe location at the remote stand.

The majority of the displacement was from the brow itself. In essence, the brow burst into the unconfined opening of the stope. The yielding-over-stiff ground support system once again protected the opening from greater damage. Only the wall corner was rehabilitated, the brow area was left unsupported and remaining stope mucked out remotely from 15 m back.

The system's effectiveness was proven by examination of the wall displacement. The area had previously been shotcreted, but not screened due to logistical problems of bolting corners with the hydraulic bolter being used. The brittle shotcrete system violently spilled out of the high grade sulphide bulking beneath, stopping only where the #4 mesh installed with the (fs46™) friction set was installed (refer to Figure 17), proving its value as enhanced support system.

Figure 16 Back and brow of 7896 bottomsill following rockburst

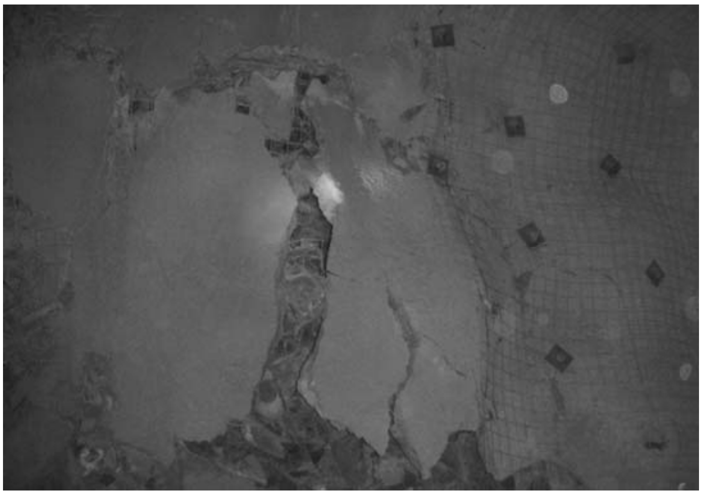

Figure 17 Unscreened corner of brow following rockburst

11 Discussion

The 4 point MPBX and instrumented cable bolt locations are installed in close proximity to one another. The load in the cables will build up in response to ground movement. The rate at which the load builds in the cable for each mm of ground movement depends on the support stiffness. For a stiff support system the load will build up much quicker than for a support system designed to be softer. Along its length, the cable will load up most where the rock mass strain (i.e. the slope of the spatial ground displacement graph) is highest. Prior to the 2.3 Mn event which destroyed Detect Cable #55, all the deformation was concentrated within 3 m into the back. At the adjacent MPBX #64, as expected, loads built up in the first two load points of cable #55. Prior to the break, this movement was <1.5mm, while load in the cable was 2 t, indicating that the cable was behaving as a 'stiff' support system (refer to Figure 14). The cable stretched with the rock and (Hyett, A.J., 2008), 'went along for the ride' until the magnitude event destroyed it. The electronics of the cable were still working, failure response, typical when wires to the load meter are ruptured within the cable, indicated rupture occurred between load meters 1 and 2 (1.2–2.7 m).

MPBX #64 temporal plot shows a significant amount of movement between readings at three points in time during the study, early, mid, and late 2008. These include the cable failure, retreat of the receding pillar towards the instrumentation, and a further retreat which brought the mined opening within 2 m of the instrumentation.

Unfortunately, instrumentation had not yet been installed in the topsill area nearest the panel when the 2.6 Mn event occurred March 13, 2008. Only minor changes were recorded on the topsill location further away from the source location of the event. This in itself was interesting as most damage in the form of peeled shotcrete occurred beyond the panel area where screen had been installed over the shotcrete arches.

11.1 Early 2008

Following failure of DETECT Cable #55 (early 2008), about 8 mm of movement occurred between the head and the 1.2 m anchor and another 5 mm between the 1.2 m anchor and the 2.7 m anchor with less between the deeper anchors. The greatest deformation occurred in the immediate back, within the first 4m into the sill. With a total of 16 mm of deformation, the ground support system performed as expected, minor cracking of the brittle mesh re-enforced shotcrete was well contained beneath the #4 gauge screen installed with 46 mm friction sets. Interestingly, following the initial displacement at the 1.2 m anchor following the 2.3 Mn event, values began to decrease.

The bond between the instrumented cable and grout was very good. Even though the ground was broken-up, the operator pumped three bags of grout into each hole upon installation, whereas commonly, cable installation would only take one bag. Debonding would typically result in break-up at the contact and allow cable slip relative to the rock, resulting in less load increases for each mm of ground movement. In the readings after the seismic event, there is an order of magnitude increase in the deformation (1.5 mm to 16 mm) The 14.5 mm movement alone would be expected to significantly load the cable given its initial stiffness, and any dynamic effects would be superimposed on top of this.

Physically underground in early 2008, the mining excavation was approximately 24 m from the instrumentation. Small cracks were observed in shotcrete sandwiched under mesh, but the excavation remained intact.

11.2 Mid 2008

As the mining front passed the second set of instrumentation installed a short way into the footwall at the bottomsill, no further increases to load/displacement occurred. Cable #56 and MPBX #66 registered 5 ½ t and 4.5 mm of displacement respectively. Again, the first two load points of the cable registered load (4 and 1.5 t), 3.5 mm of that total was at the first load point. It can be seen that blasting and a 2.1 Mn event contributed to this load, but did not have a significant impact at this monitoring location.

Displacement at the existing bottomsill MPBX #64 continued to increase as the 7836 mining front advanced. Following the crown, but before advancing the front with the slash, no further displacement of the first load point was observed, that displacement reading had gradually decreased to 3 mm relative to the head. The second (2.7 m) reading increased 14 mm, and the third (4.3 m) showed 3 mm for a total of 31 mm of movement. Following the slash, a great deal more displacement was observed. Once again, first reading slipped, this time to zero, or a slightly negative reading. The second (2.7 m), third (4.1 m), and now fourth (6.1 m) reading reveals 25 mm, 5 mm and 1 mm movement accordingly for a total of 31 mm of movement. At this point, an ever increasing deformity of the back resulting in 'cracked shotcrete' was observed beneath the mesh. The mesh was beginning to stain under the friction set bolt plates, but no damage to these components were observed.

At the topsill, displacement at the tapering crown pillar between 3320 and 3350 Levels increased with the mining. The crown had not yet undercut the area and displacements were 2 and 8 mm (1.2 and 2.7 m). As the sill was undercut, displacement increased to 5 and 13 mm and later to 5, 17 and 3 mm (4.3 m). With time, the rate of increase slowed down especially after the panel was filled.

To the north, instrumentation revealed little change in corresponding load (less than ½ t) to a final total of 7 mm of displacement when the MPBX was destroyed due to reconditioning (screen-over-shotcrete). A 2.1 Mn event in the vicinity knocked down shotcrete from the unscreened shotcrete arches installed at the topsill. Extension of screen over the arches, a continuation of work already completed over the previously mentioned panel area, destroyed the instrument.

11.3 End 2008

With the first 7896 production blast in late 2008, MPBX #64, now situated two meters from the open stope, measured extensive displacement. All four readings increased to over 90 mm. The shotcrete under mesh was severely shattered and radial cracking of shotctrete could be observed with visual bulking of the back near the east shoulder. There was no damage to any of the (fs46™) friction set bolts. They were holding as per design, at this point, #4 gauge strands were squeezing under the face plates. The 2.6 Mn event occurred just as the stope approached crown position.

In the topsill, two instruments, MPBX #65 to the south, and DETECT® Cable #52 undercut by 7896 mining survived. Little change is observed for #52, only ½ ton, even when undercut. A reading was never obtained for #65 due to the open-hole condition.

12 Correlation of modelling and instrumentation results

Numerical modelling analysis correlated well with instrumentation data in the active mining front. It showed that as the pillar receded, stresses increased in the pillar. The model was not able to replicate the effect of the aplite dyke. This is readily observed in Figures 2 and 3 whereby the larger magnitude seismic events plot outside the immediate mining area, lining up with the known geological features as opposed to the homogenous assumptions of the modelling. In reality, the stiff dyke generated larger events due to the high UCS in comparison to the ore zone and the surrounding metasediments.

Prior to 2007, significant rockbursts occurred in the topsill area. Numerical modelling revealed that the tapering crown pillar loaded up. The pillar was seismically active during the development cycle and rockburst conditions were experienced during development of the topsill below the main level horizon. Left alone, the area was not seismic, but with mining, the seismicity was triggered. In late 2007, prior to the installation of enhanced support, several failed mechanical bolt face plates were observed in the back. The 6.35 x 125 mm square plates bent under load, splitting from plate-edge to centre-hole location. Microseismic source locations and shotcrete shards suggested stress was still evident in the pillar above the topsill.

Instrumentation was in place in time in 3350 Level for the last two stopes to be mined, one in the topsill above 7836 Stope, the other in the topsill above 7896 Stope. Both locations were undercut by mining, the difference between the two locations can be readily observed with instrumentation results. Little loading or displacement was found at the 7896 intersection end (0.5 t/7 mm), while at the 7836 end, increasing displacement occurred as the instrumentation was undercut. 10 mm occurred as the crown was blasted (not completely undercutting the sensor location), an additional 8mm when undercut with the slash, and a further 7 mm until the panel was filled (25 mm in total). Following filling, displacement 'creeped' a further 8 mm to 33 mm. The only difference in ground support in the two test areas was the fact that the intersection (7896) had been cable bolted whereas the sill (7896) had not. Cable bolt response did not allow any movement to occur at the intersection location and the stiff system was appropriate to hold up the ground. Meanwhile, yielding support held broken shotcrete together at the surface. At 7836, the back was failing due to gravitational effects. The shotcrete arches worked well initially but they were ineffective when they were undercut. Once filled, due to the confinement offered by the hydraulic fill, the rate of displacement slowed accordingly.

13 Conclusion

Ground conditions began to noticeably deteriorate as the amount of rock movement increased and as the extraction approached +90%. Deterioration was effectively controlled by adding a yielding support component to the stiff support system. The amount of movement the system absorbed was effectively measured with monitoring stations. Where the enhanced, yielding support system was installed, no reconditioning was required. The system in place performed effectively and withstood all the major strainburst events up to 2.6 Mn magnitude, completely eliminating production delays and damage from seismic events.

For protection against the dynamic stress effects due to rockbursting, a stiff (holding) and yielding ground support combination is required. Results reveal that displacements of over 90 mm were controlled from severe rockburst damage due this combination effect, 35 mm began to reveal loading of the yielding support system and at 15 mm damage began to be observed to the stiff support system beneath mesh. The layer of #4 gauge screen installed with (fs46™) fiction set bolts over primary ground support was costly up-front, yet it proved cost effective for the life of the extraction. Fracturing and ejection of shotcrete was very common during earlier production drilling and raise boring operations but was later contained and eliminated with the yield-over-stiff system. Most importantly, the workers in the drilling, blasting and mucking operations expressed confidence in the ground support and extraction design.

Insight into what was occurring in the rockmass and why the support system works as well as it does, is supported by the instrumentation results as well as visual observations. The 2.3 Mn event resulted in an increase in displacement following the event at all instrument points. Subsequent decreases at the gauges closest to the excavation were observed following each production blast as the pillar receded. The results support the fact that while fractures further away from the excavation were opening, those closest to the surface were closing (a similar response is observed at the topsill). The driving force required to cause such an effect and close up these fractures can be explained by the fact that deeper fractures begin to relax onto the opening following each blast, just the opposite of the initial displacement following the large event. The ground is subject to an applied normal stress/pressure of the newly rehabilitated excavation. The excavation (driving force) closes previously open fractures, many of which were exasperated by the 2.3 Mn event. In contrast, instrumentation outside of the ore zone in better ground revealed homogeneous distributions along all gauge locations.

Aside from the intent of the project, it was found that a fully grouted instrumented cable bolt on its own, is ‘too stiff’ for ground conditions. The capacity is used up with relatively small amounts of ground movement, especially in burst prone ground after the dynamic loading of the cable is superimposed. After 16 mm of deformation, the ground was able to support itself, but it is conceivable that the cable capacity was used up to accommodate the ground movement when the 2.3 Mn event occurred. It had loaded to 2 t and moved 1.5 mm previous to the event. It must be noted however, that where cables were installed and plated in the bottomsill intersection, all of the cables performed well. A closely spaced pattern of high capacity, double cable bolts act together to resist movement of the ground in the first place, whereas the random single cable acted alone.

The results obtained from this project were used to plan the recovery of a similar receding pillar situation at the south end of the same orebody. Production was to be accessed through new development from the footwall. Cost of development would be largely offset by the cost of rehabilitation required to prep the existing access to the area, notwithstanding a substantial cost savings potential from uninterrupted production. Results obtained through this study substantiate the approach of a yield-over-stiff ground support system for strainbursting conditions.

Areas damaged by seismicity, where the stiff rebar system is in place have been rehabilitated with use of this yield-over-stiff system. Furthermore, the lessons learned are currently being adopted in varying forms at Vale’s Creighton Mine and shared with the other mining operations.

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