Development and Implementation of a Risk Mitigation Strategy to Mine a Primary-Secondary Production Stope in a High-Stress Environment at VALE Creighton Mine

Allan R. Punkkinen
Senior Specialist - Ground Control Creighton Mine VALE Canada

Andrew J. Hyett
Yieldpoint Inc.

ABSTACT: Safe extraction of the valued ore resource in the deep levels of VALE Creighton Mine has progressed in a pillar-less fashion using vertical retreat, slot-slash and uppers retreat methods since the cessation of ‘cut and fill’ mining in the late 1980’s. Sequencing of the panel extraction and filling has been the key to successful exploitation of high stress orebodies at depth.

In late 2010, discussions between the Operating Department and Creighton Ground Control revealed an opportunity to evaluate a trial primary-secondary sequence in the west end of the 400 Orebody at the 2340m horizon. With a separate access into the ‘secondary’ panel, personnel access could be restricted on the bottomsill, protecting workers from direct exposure to elevated levels of microseismic activity. The topsill, developed within the slag cemented tailings backfill of the previously mined production front overhead, works well in isolating workers from direct stress effects of wrap around stresses.

To manage the trial primary-secondary project, a high level risk analysis and management of change was carried out to mitigate potential danger. As part of the requirements, an instrumentation project was conducted in the hanging wall and footwall bottomsills of the secondary panel and within the secondary panel itself. The extraction sequence was modeled with Map3D® software, confirming high stress levels with the advance of the primary panel. Enhanced ground support was installed based on modelling results.

A key objective of the instrumentation project was to verify support system response to mining and to obtain knowledge in regards to the behavior of the stope. This paper describes the first time that the new innovative instrumented rockbolt technology had been used in a hard rock mining environment. Understanding of the physical deformation mechanisms of ground support in response to high stress conditions is the basis for an effective ground control strategy. The data played an important role in subsequent enhanced ground support system design at the mine and importantly, established the fact that the secondary pillar had not totally failed. Subsequent cavity monitor results helped establish that fact.

While it is unlikely that Creighton Mine will change to a full scale primary-secondary extraction sequence, the benefits of the trial, which include the opportunity for additional rock disposal, open up a realm of possibilities worthy of investigation. Calibration of the instrumentation results with visual observations of development drift stability and numerical modelling will provide further insight into ground control management as changes to mining sequences are evaluated.

1 SITE DESCRIPTION

Creighton Mine is located in the Greater City of Sudbury, 19.2 km west of the City of Sudbury. The Creighton Orebody was first discovered in 1856 and mining started in 1901 by the open pit method. The upper area of Creighton, known as No. 3 Mine, extends from surface to 580m (1900 Level) and consists of a large low-grade orebody that is mined intermittently depending on metal markets and other economic factors by blasthole and VRM methods. Ore was hoisted up No. 7 Shaft from a loading pocket at 1900 Level. Production from this area has been suspended since October 1991.

The lower area, Creighton No. 9 Mine, extends below the 580m horizon. Mining is currently taking place upwards at 1090m (3570 Level) and down-dip from 2380m (7810 Level) with remnant mining at intermediate levels. Plans are to extend operations to 1090m (3150 Level) and possibly as far down as 3000m (9,800 feet). The major mining method in this area is Slot and Slash. Current ramp development has passed 2500m, and the deepest level extraction remains at 2420m (7940 level).

Mineralization is contained within a north-west plunging embayment of norite into the footwall. Within the embayment, mineralization is controlled by two troughs or indentations into the footwall. The majority of orebodies are located along a northwest plunging trough (Creighton 400 trough) which follows the general geometry of the main Creighton Embayment, while the remainder are located along a near orthogonal trough (Gertrude 402 trough) plunging north east at 40^{o}.

2 REGIONAL GEOLOGY

The copper-nickel sulphide deposits at Sudbury are part of the Paleoproterozoic Sudbury Structure which comprises the Sudbury Igneous Complex (SIC); metasedimentary rocks of the Whitewater Group which occupy the centre of the Sudbury Basin; and a ring of brecciated Archean and Paleoproterozoic footwall rocks surrounding the SIC. The rocks of the SIC are exposed within an elliptical ring with a long axis of 45 miles and a short axis of 17 miles (refer to figure 1). The SIC is dated at 1850 million years.

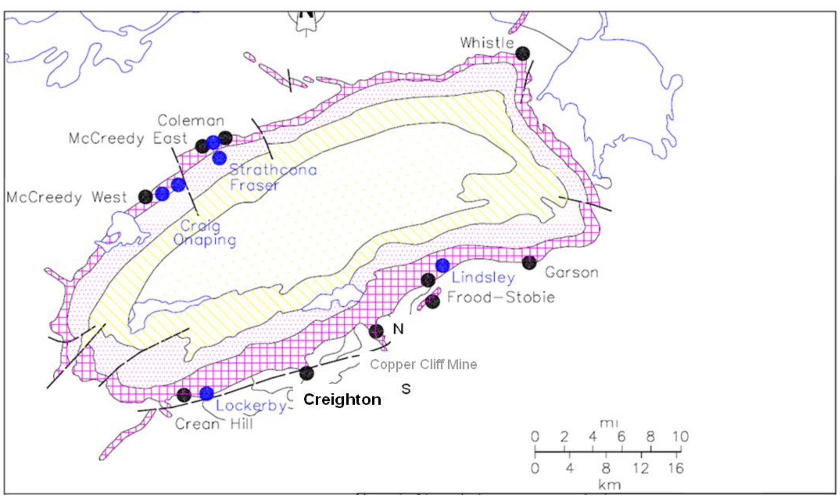


Figure 1- Sudbury basin

2.1 Local geology (current deep levels)

The Deep mineral system at Creighton Mine is the down-dip extension of the 400/6100 and 1290 orebodies below 7400 level. At depth, lower grade mineralization is contained in the 400 trough feature and hosted in norite of the SIC. Sulphide mineralization becomes concentrated along the basal contact with the granitic and gabbroic footwall rocks common in the Creighton embayment. High grade sulphide mineralization enters the footwall to the east of the contact, thinning along the 1290 shear zone.

3 INTRODUCTION

The mining sequences for all current production complexes at VALE Creighton Mine are reviewed in order to develop a set of guidelines for planning purposes. Any changes to these sequencing guidelines are approved in writing in a Management of Change Process. To manage the trial primary-secondary project, a high level risk analysis and management of change was carried out to mitigate potential danger.

The opportunity to initiate the risk assessment process and evaluate the trial primary-secondary sequence was based on two key factors. The geometry of the orebody was favourable with no rock inclusions cutting through the sulphide, and the fact that a separate access into the ‘primary’ panel was available, preventing workers from direct exposure to elevated levels of microseismic activity that were anticipated (geometry is shown in figure 2). Otherwise, the project would not have proceeded. It was also agreed that enhanced ground support, consisting of #4ga mesh over existing shotcrete would be installed at the topsill and footwall drift on 7535 level (2296m), to protect against the effects of seismic shaking under the previously filled panels from 7400 level (2255m).

A series of defined mitigating measures proposed by the team to address high to moderate risk levels defined in the risk assessment process were effective in addressing the major concerns. The assessment is a measure of the likelihood of an undesired event occurring against the possible consequence. The risk levels are measured before and after mitigation (refer to figure 3). It was understood that a possibility of excess dilution might be a consequence of such a change, as part of the action items put forth, an extensive review was set in place to model and verify the assumptions.

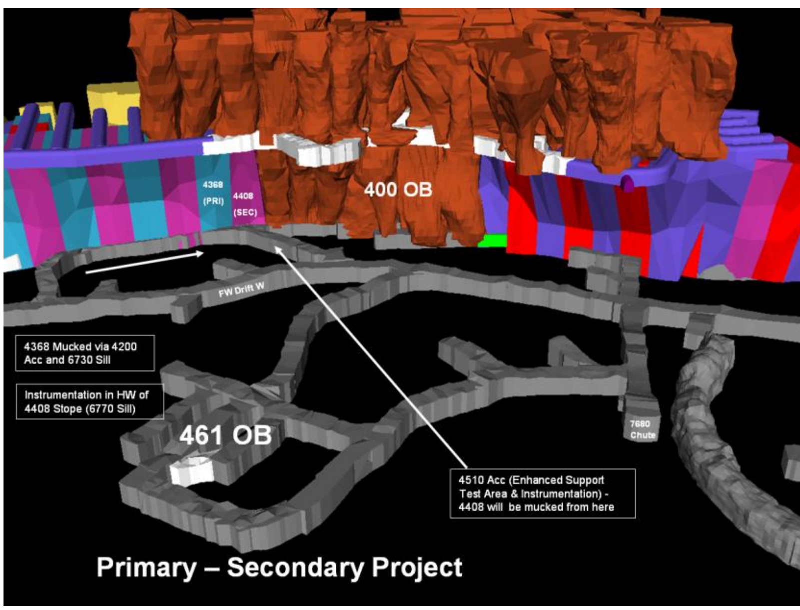


Figure 2: Mining geometry.

Likelihood	Low	Minor	Moderate	Major	Catastrophic
Certain	0	1	0	0	0
Likely	0	0	0	0	0
Possible	0	3	4	2	0
Unlikely	0	0	4	0	0
Rare	0	0	1	0	0
	Consequence				

Residual Risk - After Mitigation

Likelihood	Low	Minor	Moderate	Major	Catastrophic
Certain	0	0	0	0	0
Likely	0	0	0	0	0
Possible	0	6	0	0	0
Unlikely	0	0	1	0	0
Rare	0	0	0	0	0
	Consequence				

Figure 3- Risk Matrix

4 NUMERICAL MODELLING

To obtain an idea as to expected stress changes during the mining extraction phase, linear elastic modeling was carried out using the program Map3D®. A shear (deviatoric) stress value of 70% of the uniaxial compressive strength was used to indicate failure. UCS values for massive sulphides average approximately 135 MPa, and surrounding granites, 240 MPa. After mining of the initial primary stope, zones of high deviatoric stress, low confinement with large displacement are assumed as having failed. Figure 4 reveals the distribution of shear stress following the extraction of the primary stope with instrumentation locations superimposed on the stress grid slice. In ore (i.e. topsill pressure cell location and 6770 Sill), the failure zone is inferred at 95 MPa but is substantially higher at 170 MPa in rock (FW Dr and 6730 Sill). Behaviour of the support system was observed visually while displacements were verified by the instrumentation.

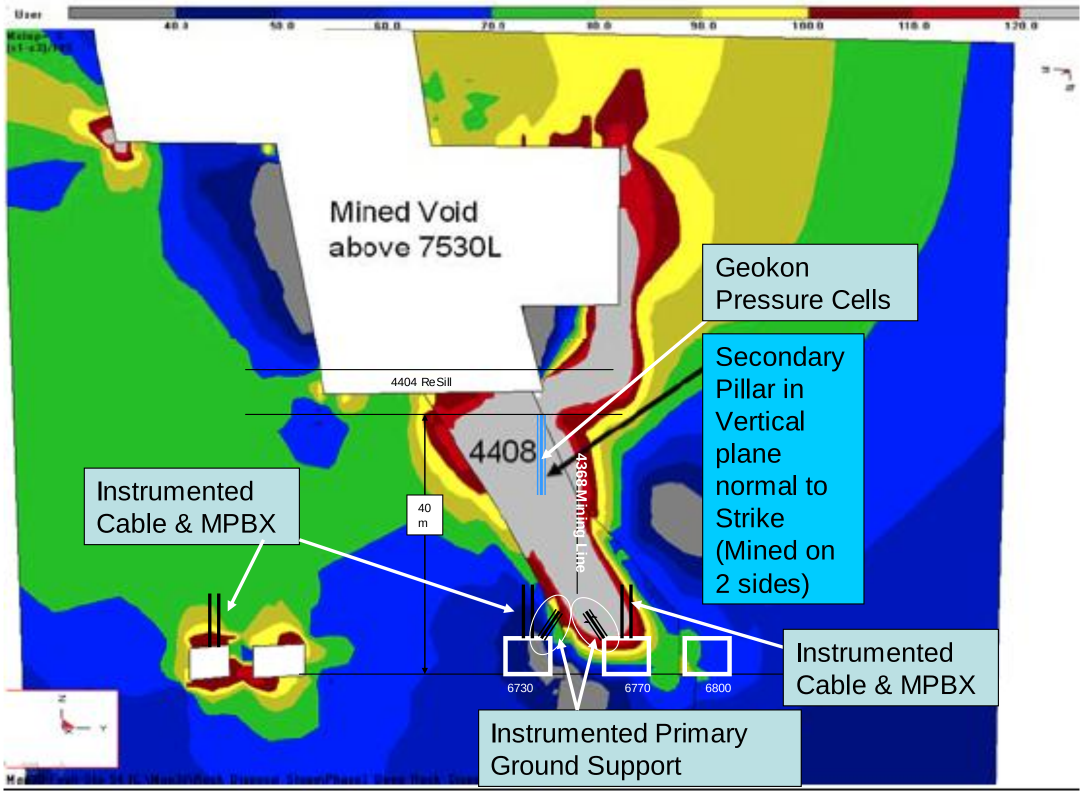


Figure 4 - Deviatoric Stress (σ_1- σ_3) at Diminishing Pillar showing instrumentation locations

5 MITIGATING MEASURES

The risk review in regards to leaving a rock stope in the 400 OB West Orebody from 2296m to 2340m (7535-7680 level) identified several ground control related mitigation strategies for reducing the level of risk. To measure the impact of excessive local seismic activity as the 4408 panel yields, an instrumentation strategy using DETECT^{TM} instrumentation components and Geokon^{TM} Borehole Pressure Cells (BPCs) were installed at the top and bottomsills to support the numerical modelling work carried out.

The following types of instruments were deployed: 6.1m instrumented cablebolts (d-CABLE), multipoint extensometers (d-MPBX), 2.4m instrumented rebar versions of Jennmar Corp's (d-REBAR), and instrumented versions of Mansour Mining's MCB 33 (d-CONE).

Access to the secondary stope vicinity was restricted when production at the primary stope began and a procedure was implemented to prevent entry into the area to eliminate personnel exposure. Instrumentation, designed for installation in the restricted high stress area, was wired with long conductors and read with the use of data-loggers from safe locations. A series of long boreholes designed to be drilled approximately

2/3m apart in a planned attempt to pre-shear the rockmass ahead of the hangingwall boreholes at the 4408 (secondary) and 4368 (primary) panel prior to production was subsequently abandoned due to lack of real-estate at the development headings at the topsill. An alternate plan to drill and blast destress holes in the event seismic activity affected ground conditions or adverse squeezing occurred in the boreholes was put in place. As part of the plan, screen was installed over existing shotcrete with yielding ground support components to prevent damage from seismic shaking. The blast-holes were not required.

To further reduce the impact of dynamic stress response as a result of high peak particle velocities due to blasting, electronic detonators were used for the final crown blast to maximize timing and minimize ppv. Blasts fired with nonel (non-electric) detonators, were limited to 2000 lbs or 200 lbs/delay to reduce the occurrence of large seismic events and damage to the 4408 secondary pillar as the primary panel was mined.

To address the possibility of higher sandfill and hangingwall dilution when mining 4408 (secondary) Stope, it was agreed that the primary stopes, 4368 and later, 4367 would be filled with a stronger binder recipe of 20:1 slag/cement blended binder for the body of the stope with a top-up under the pillars at 10:1 to consolidate. Cemented hydraulic fill from classified tailings is poured at a density below 68% solids by weight with limits for rock disposal. It was understood that assumed failure could occur on the opposite side at 4448 Stope (25:1) due to a large amount of waste rock which had been placed under the pillar, although conditions would remain the same whether or not 4408 was taken as a primary or secondary stope.

With all of the measures in place, 4408 Stope was designed as a rock disposal panel following a plug height design that would allow rock disposal into the stope body without interference when developing underneath for future topsills. Rock fill placement was hastened to prevent sand and rock dilution. Time open effect has been documented as directly proportional to the amount of hangingwall dilution.

6 INSTRUMENTATION

The instrumentation project was conducted during the mining of the 4368 primary stope to 6730 bottomsill until the point that mining of the hangingwall section cut-off access to instrumentation and preparation for mining of the secondary stope prompted removal of the pressure cells at the 4408 topsill. Instruments were installed in three locations in and around the secondary pillar as shown in figure 5.

<u>7680 level:</u> 3 x MPBX, 3 x Cable, 2 x Rebar 1, x MCB33
The instrumentation results presented were installed at two locations prior to the project, to the footwall and in the ore zone of the secondary pillar. The ore zone (6770 Drift) was located north of the 4368 mining line, cut off when mining the primary stope hangingwall section (4367) as mentioned above. A previously installed instrumented cable bolt and mpbx were installed in the footwall drift.

<u>7535 level:</u> 2 x BPC
2 GEOKON Borehole pressure cells (BPC’s) were installed from the 2296m overcut (7535 level) 10m down into the pillar at the centre of the secondary stope to measure stress changes as the primary stope was mined.

7 MONITORING PROGRAM

This project represents the first time that the new instrumented rockbolt technology had been used in a hard rock mine using hard rock mining equipment. All previous installations had been in U.S. coal mines. During the course of production, data-loggers were installed on instrumentation to monitor changes, in particular changes following production blasts and subsequent microseismic activity in the high-stress environment. Following the 5th production blast in the 4368 Primary Stope panel, a 1.7Mn event occurred. Following this event, measurements from the instrumented rockbolts indicated significant changes and revealed a great deal as to support performance.

The instrumented rebar and MCB33 were installed with 30mm resin using a MacLean bolting machine into the shoulder of the footwall and ore headings on 7680 level. The MCB installation was not successful in the FW. Difficulty of installation in the footwall required the rebar faceplate to be manually tightened between 1-2 tonnes in the heavily fractured heading. Both the rebar and mcb were pre-tensioned by the MacLean bolter in the ore heading. All holes were drilled through shotcrete. Figure 5 shows the effect of subsequent stress changes at the shoulder location of the 6770 Oresill heading. The instrumented rock-bolts were installed in the “shoulder” of the heading where shotcrete spalling is observed, and the extensometer and instrumented cable installed in the back. The d-MPBXs and d-CABLEs were fully grouted with the use of a pump and grout hose inserted to the top of the borehole. Installation methods for rebar, MCB and cable instrumentation were identical to those used by mine operations in the bolting operation.

Two borehole pressure cells (BPC’s #091 and #092) were installed in 10m long, 150mm diameter production holes in the 4408 Stope at 7535 level. Provisions were taken to ensure that the gauge was ‘reasonably” centered (+/-13mm) in the borehole. The location and orientation of the cells are shown in figure 6 which represents a plan view. 091 was aligned transverse to the stope, to measure the longitudinal pressure change, and 092 longitudinal to measure the transverse pressure change. The orebody denoted by “MINED” was extracted during the course of the project and exhibited high stress at the topsill. To the east, the 4448 Stope was tight-filled with a hydraulically placed, 25:1 slag-cement mix and mine tailings with waste rock addition. The topsill was subsequently tight-filled with 10:1 to provide additional support under the pillar when additionally undercut by secondary stope mining.

Figure 5– 6770 Oresill Instrumentation ‘squeeze’

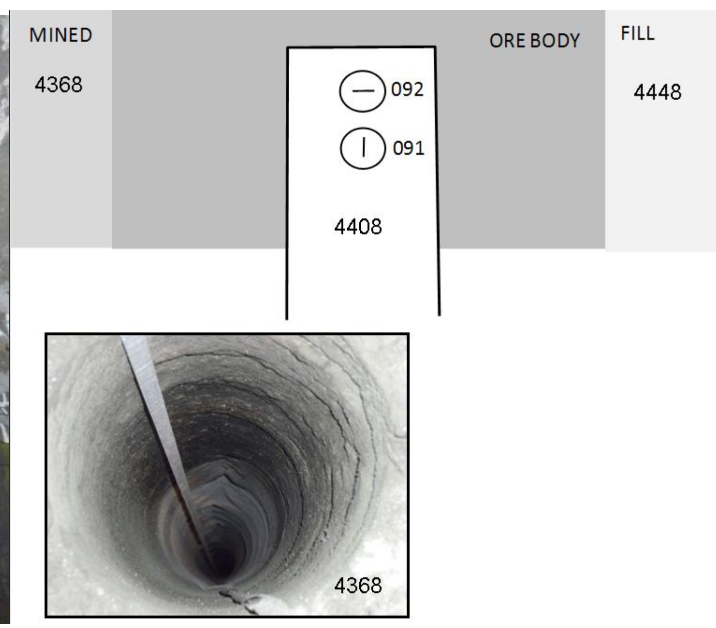


Figure 6 – 4408 BPC Orientation showing 4368

Although the BPCs were designed to be installed in 56mm boreholes, as opposed to 150mm production holes, hollow inclusion theory states that the stress changes in the soft cement inclusion should be constant throughout and hence independent of borehole diameter. In fact, the effect of the soft cement inclusion was seen as advantageous due to the extremely large stress changes expected to occur during the experiment. Prior to installation, minor borehole breakouts indicating high levels of differential stress

VALE Inco, Creighton Mine MTS, Copper Cliff, Ontario, P0M 1N0 - PHONE:(705) 692-2130 -FAX 692-5778

in the primary stope were observed in the hangingwall oresill holes of the primary panel being drilled (refer to figure 6).

During installation, the cells were encapsulated with 2.5m depth of 0.40 w:c ratio grout into wet holes which could not be pumped or blown out and special care was taken to ensure that the cells were oriented correctly. A centering device was developed so that the cell would be reasonably centered in the borehole and a generous layer of duct tape was wound around the stainless steel pressure tube to mitigate the risk of damage to the pressure tube from shearing in the rock. The borehole pressure cell was inflated one week after installation. As expected, the pressure in the BPC relaxed and subsequently re-pressurized to approximately 40MPa. Borehole pressure cells used in this project were set-up to measure pressure changes as the stope was mined upwards from the bottomsill location and revealed corresponding stress changes as the panel was excavated. Results are collaborated with the breakout of the primary stope and effect on the secondary stope geometry following production.

8 INSTRUMENTATION DATA ANALYSIS

8.1 <u>6770 Oresill MPBX (100651003) and Cable</u>

Following the 5th blast (1.7Mn), 0.8mm of movement was measured by the MPBX located in the back at the centre of the tunnel (figure 7). This movement is located beyond 3.2m into the back rather than at the excavation surface as seen in figure 8. The adjacent cable bolt did not show any corresponding load which is consistent with the very small amount of movement recorded by the extensometer.

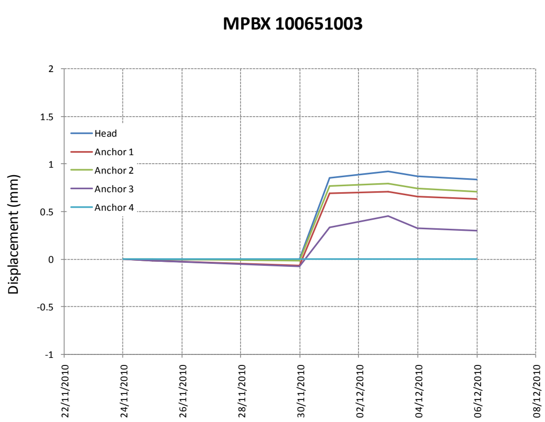


Figure 7: Displacement versus time

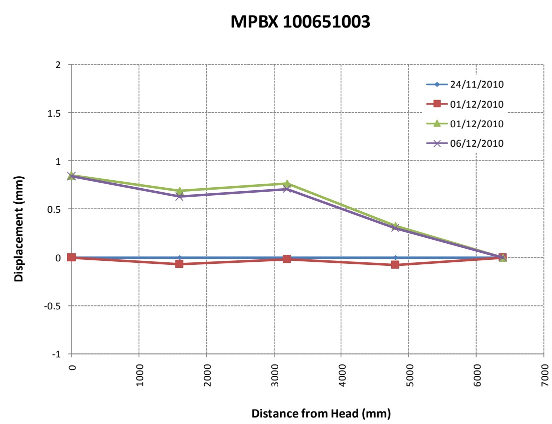


Figure 8: Displ. Distribution along length

8.2 <u>Instrumented Oresill Rebar (100975102)</u>

The resin rebar was tensioned with a MacLean bolter to an initial pre-load of 4-5 tonnes measured at the strain gauge nearest the plate (gauges 1 and 4 in figure 9). As mining proceeded, the resin rebar exhibited load changes in response to incremental mining steps and again the most significant load increase was observed following the 1.7Mn seismic event (step in figure 9). In fact, this event was sufficient to exceed the elastic limit (2500$\mu\varepsilon$) and cause yield along the part of the rebar nearest the plate. The strain at this point suddenly increased to beyond 6000 $\mu\varepsilon$ or 0.6% strain.

Thereafter, the yielded sections (highest profiles in figure 9) exhibit progressive creep whereas the elastic sections of the bolt towards the toe of the hole do not. As indicated by figure 10, the highest load/strains were measured closest to the plate: the yield strength of the steel being exceeded over a 1m length. The corresponding end to end stretch of the rebar is 3.5 mm (figure 11).

The load-strain curve for the rebar based on QA pull tests is supplied courtesy of Jennmar Canada. A typical 20mm rebar yields at .25% strain, exhibits perfect-plastic behaviour between 0.25% and 1.25% strain and begins hardening beyond 1.25% strain (figure 12).

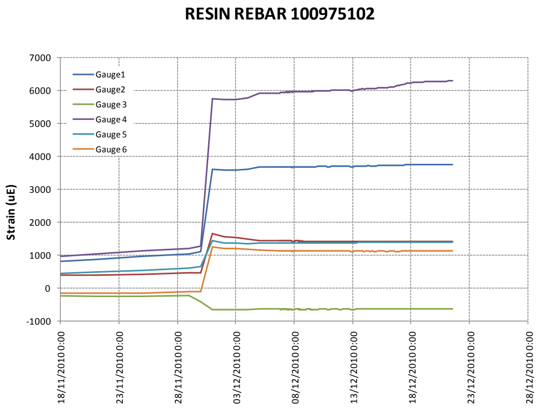


Figure 9: Strain displacement versus time

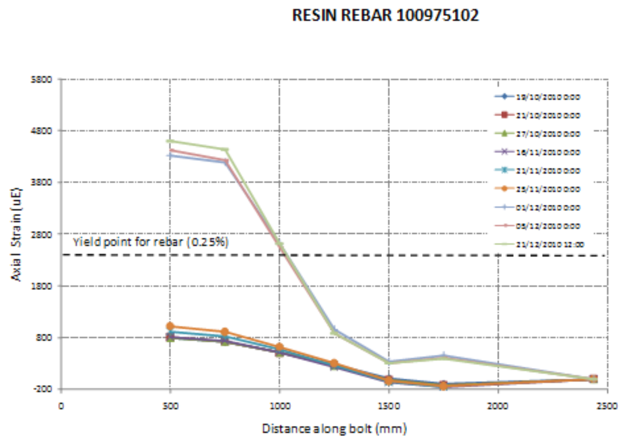


Figure 10: Axial Strain distribution along bolt

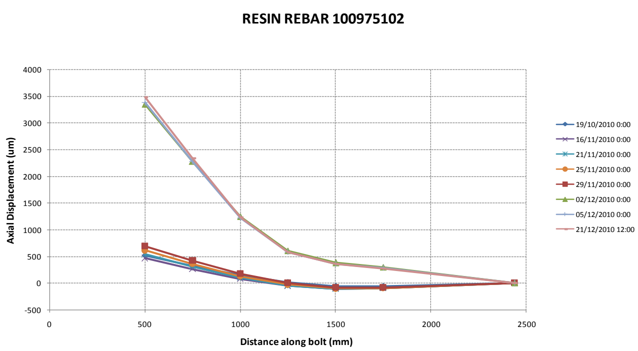


Figure 11: Stretch along the resin rebar

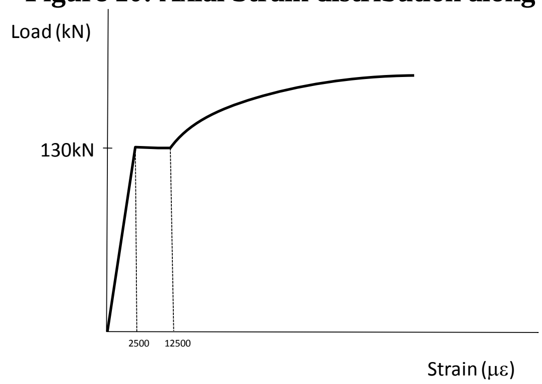
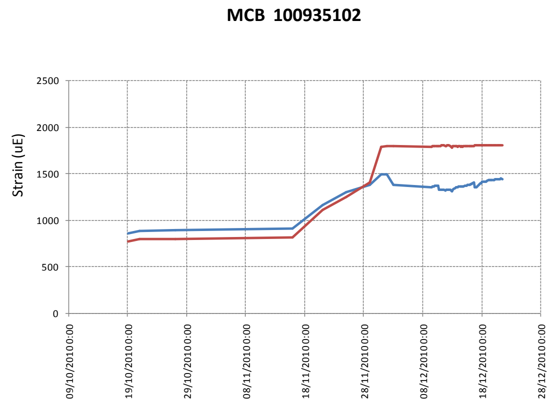


Figure 12: Load-Strain curve of rebar

8.3 <u>Instrumented Oresill MCB (100935102)</u>

The MCB indicates an initial pre-tension in the order of 4-5 tonnes, very similar to the nearby resin rebar. Figure 13 shows the response of the MCB to mining. Like the resin rebar the MCB displays a significant increase in load associated with Blast 5 and the associated 1.7Mn seismic event, with the divergence of the two plots (which represent diametrically opposed strain gauges) being related to bending or shear of the bolt.

Whereas for the resin rebar the increase in load resulted in yield of the steel, for the MCB the strains do not exceed the yield-point of the steel. In other words, the MCB is absorbing the rock movement by deformation of the resin annulus rather than by yield of the steel. The bolts were installed in close proximity to another (refer to a figure 13 for a comparison).



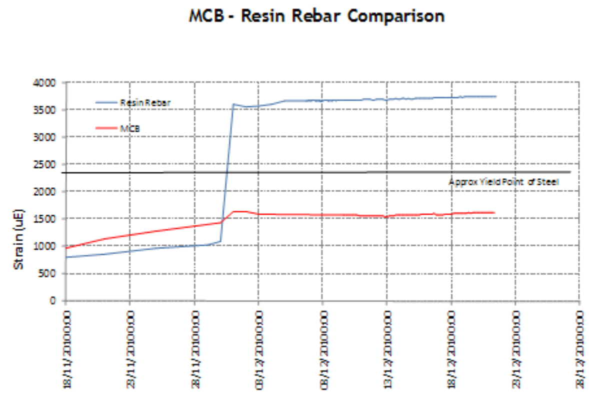


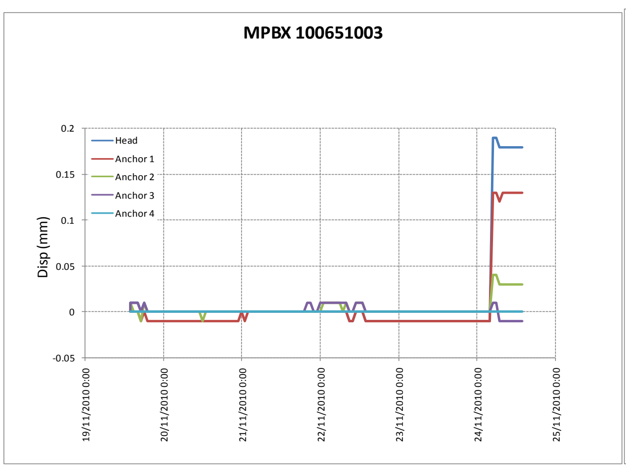
Figure 13: Strain displacement versus time MCB

Figure 14: Comparison of Rebar & MCB

8.4 <u>6730 Sill MPBX - Rock (100651003).</u>

The extensometer was logged with a SLUG™ data-logger during the first blast which clearly corresponds to a step in the displacement profile. Although the magnitudes of deformation are very small, only 150mm over the 21ft extensometer (refer to figure 15) it is apparent and that the movement is relatively evenly distributed over the entire length of the extensometer with the head at the excavation surface exhibiting most. Such small deformations are probably driven by elastic deformation in response to mining induced stress changes.

However, subsequent manual readings indicated an important change as mining of the stope proceeded (Figure 16). As the MPBX deformations increase (after the 2nd blast on 25/11/2010) the displacement pattern changes from being evenly distributed to being localized between anchors 1 and 2. In fact there is almost no deformation between anchor 1 at 1.6m and the head at the immediate back. All the deformation that accumulates during blasts 2, 3 and 4 are localized within a single interval (between 1.6m and 3.2m). Finally after Blast 5 (and the subsequent 1.7Mn event) the MPBX reports with just anchor 1 (at 1.6m) intact. It is suggested that the localized shear movement has damaged the extensometer between anchors 1 and 2. Anchor 2, at 3.2m is beyond the length of the dense array of the 2.4m length primary support, suggesting the shear movement occurred just beyond the primary support components. For subsequent readings, the deformation between the head and anchor 1 (which had been zero prior to blast 4) increased to >4mm.



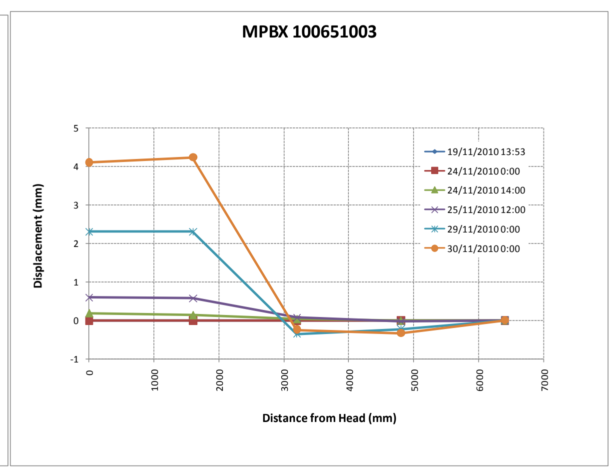


Figure 15: Displacement versus time

Figure 16: Displacement Distribution along length

The nearby instrumented cable also ceased to report after this event. This may have resulted due to damage of the instrument. In assessing this it should be pointed out that the strain gauges used in the

DETECT™ cable are identical to the technology used in the instrumented rock bolts, all of which survived the event. The cable did not report any load during its operation suggesting the increases in displacement by the MPBX were in shear.

8.5 FW Resin Rebar (101175102)

The resin rebar installed in the FW heading was installed into ground that was broken near the borehole collar making insertion of the resin cartridges difficult. It was not pre-tensioned using the MacLean bolter. Approximately 1 tonne of load was applied manually to the plate. Similar to the Oresill resin rebar to the hangingwall, the response of the FW rebar over time shows a dramatic increase in strain/load following the 1.7Mn event (Figure 16). However, this rebar, installed in the 6730 sill rock heading exhibits a completely different load distribution (Figure 17). Having been manually tightened, there is little load near the faceplate, and the maximum strain/load occurs at 1.5m depth along the rebar. Similarity as was observed with the MPBX observations, it is apparent that the bulk of the displacement occurred towards the end of the existing primary support installed in the area (gauges 3 and 6 in figure 17). The bulk of the displacement in relation to the 2m length, yielding friction set support installed in shoulder occurred at 1.5m, with little load/strain at the end of the bolt. Heavy support including wire mesh over shotcrete contributed to securing the fractured rock in the immediate "shoulder" and concentrated dominant mining induced ground movements beyond 1m into the shoulder.

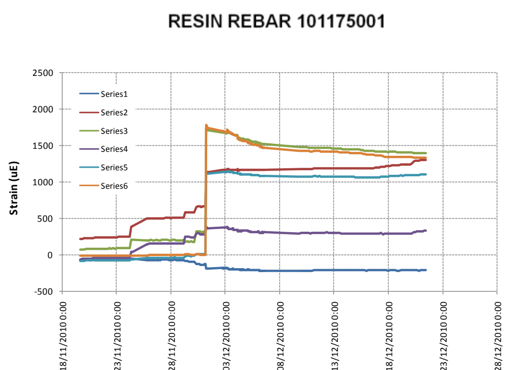


Figure 17: Strain versus time

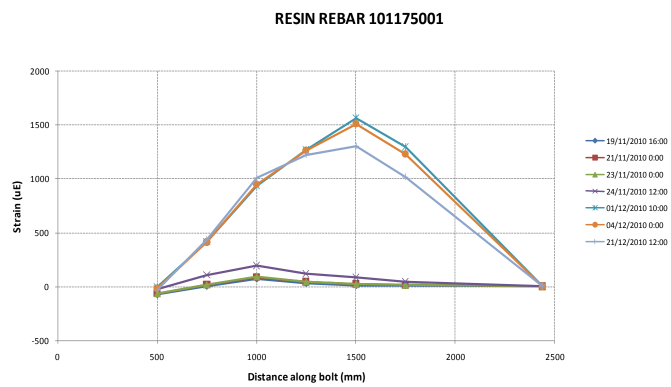


Figure 18: Strain along the length of rebar

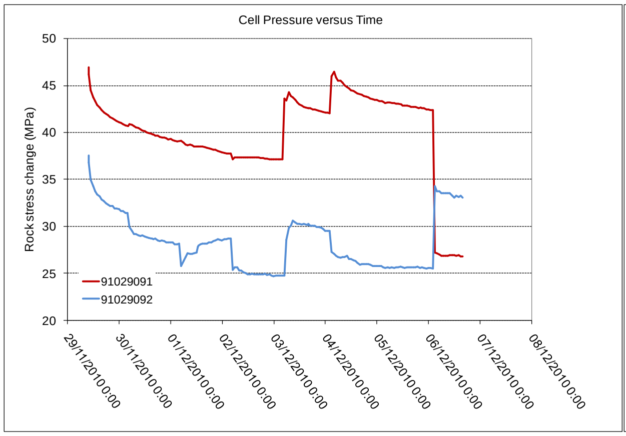
8.6 7535 level BPC Results

Figure 19 indicates the response of both BPCs, with 91029091 oriented to measure the longitudinal pressure change, and 91029092 the transverse pressure change. Immediately prior to the monitoring period both BPCs were pumped to approximately 40MPa, and the subsequent asymptotic decrease in pressure over the next couple of days is related to the relatively low strength of the cement grout after 12 days cure. The almost identical initial response for both gauges was interpreted as an indication of good, consistent installation. Subsequent steps in BPC pressure are related to definite mining events.

The corresponding stress changes inferred for the far-field rock are shown in Figure 20. As a rough initial approximation based on soft inclusion theory with the appropriate parameters, these have been calculated using the following stress reduction factor based on the relative material properties of the rock and the cement (stress change in rock or 'sulphide' = 3.0 x stress change cement inclusion).

The secondary pillar (at least its centre) was able to support a differential stress change of +80MPa (-60MPa longitudinal stress drop combined with a 20MPa transverse stress increase) when the adjacent primary crown was mined suggesting that it possessed a significant degree of integrity. If both gauges had measured a decrease in rock stress then it could have been surmised that the entire pillar was in a post-peak deformation state. Elastic modelling indicates that the shear stress levels exceed 70% of the uniaxial compressive strength which would indicate failure be inferred at 95MPa. The instrumentation and observations reveal otherwise, a calibration of the model parameters or assumptions is required with details of the plot stress changes.

Changes in the observed stresses are associated with the production blasting, and the 1.7Mn did not have an adverse affect at the topsill. The most significant and revealing change occurred when the adjacent stope crown was removed. Magnitudes are within reason and indicate a 60MPa stress decrease in the longitudinal pressure and a corresponding 20MPa increase in the transverse pressure.



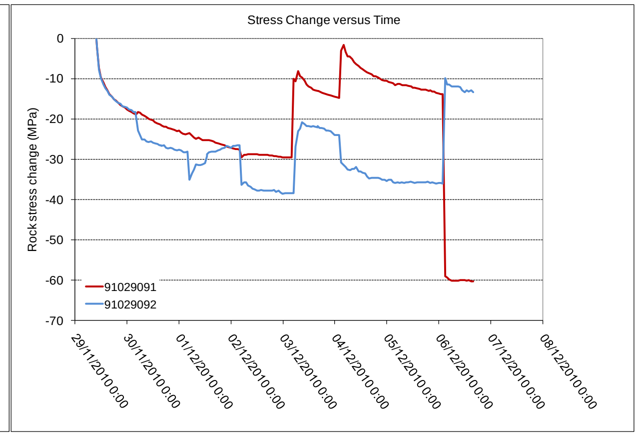


Figure 19: Time vs. longitudinal (091) and transverse (092) stress change record.
Figure 20: Rock stress changes corresponding to the BPC pressures.

9 DISCUSSION OF RESULTS

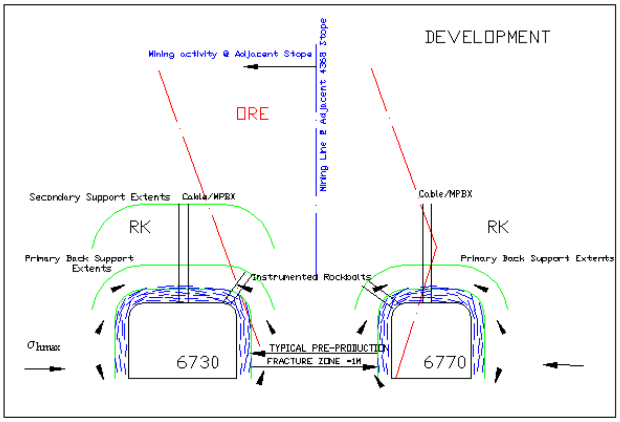
9.1 <u>6730 Sill - FW Extensometer and Instrumented cable:</u>

From a geomechnical standpoint the extensometer response represents a very characteristic stiff brittle response with the deformation pattern being controlled above the primary support limit. Following Blast 5 and the subsequent 1.7Mn event, the movement was sufficient to damage the MPBX between the 1.6m and 3.2m anchors, most likely just above the 2.4m primary support. There was little distribution of load within the primary ground support 'beam' around the opening.

9.2 <u>Paradox between different instrumentation in Oresill Instrumentation.</u>

The oresill instrumentation in the hangingwall indicates a notable contrast in response between the instrumented bolts in the "shoulder" of the heading and the Extensometer and Instrumented Cable in the back. Such variability is not unusual since the movements which are being measured and which generate load in the support element are often localized or manifest along discrete fracture planes. As time and mining proceeds, the propagation and coalescence of these structures becomes apparent and the over-arching deformation pattern more evident in the instrumentation data.

To address the current paradox consider Figure 21 which assumes that extensile cracking occurs primarily near the free surface: accordingly convergence should be measured at all points around the excavation. Measurements at Creighton agree and reveal that the fracture zone in high stress ground does not typically exceed 1m past the excavation surface at development headings as shown. In this case we would expect to observe all the support elements begin loading up near to the excavation, had the instrumentation been installed at the development stage, these observations would have been made. However, the instrumentation results obtained for the Oresill at the production stage, suggest the behavior of the excavation to the mining induced stress may be somewhat more complex and furthermore "progressive" in nature.



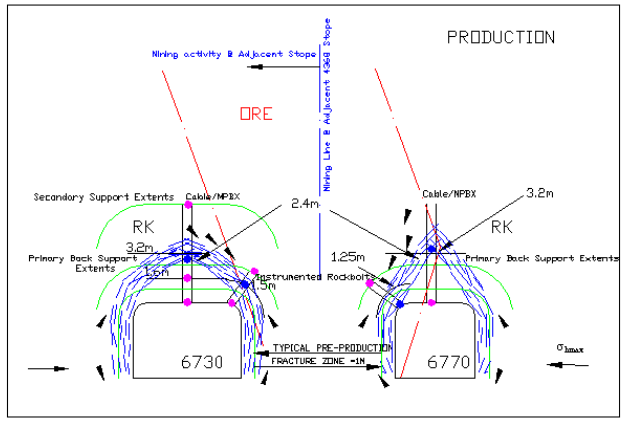
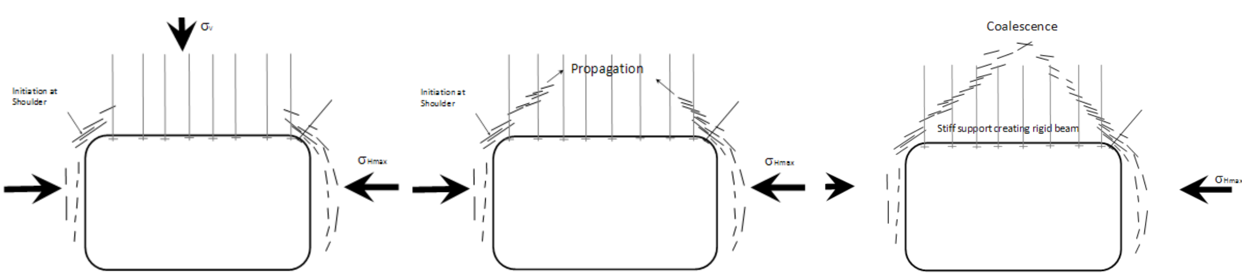


Figure 21: Induced fracture pattern around a development heading Creighton Deep
Figure 22: Induced fracture pattern around development headings production & 1.7Mn event

Figure 22 outlines an alternative model for a deformation pattern that better agrees with the instrumentation results. Further deformation initiates at the shoulder of the excavation at both excavations, although maximum shear is found near the faceplate in the 6770 (Oresill) and at 1.5m at 6730 Sill. This is probably accentuated by the relatively stiff resin rebar support in the back which will effectively suppress extensile cracking. Owing to the high ratio of σ_{hmax} : σ_v, fracturing may be more likely to propagate away from the shoulder along a path of high shear stress as mining progresses. This could explain why the 6770 extensometer measures only small amounts of movement that is deeper than 3.2m into the back. Height of primary ground support is 2.4m. The role of the support system in the shoulder and in the back close to the shoulder will be to interfere with progressive propagation of these shear fracture zones. Since the zone of fracture development is inclined but will undergo loading at different depths along their length, over time conjugate shear zones may intersect and coalesce defining a wedge shaped block in the back. Of course this block will be pinned by the high confining pressure in the back until the secondary stope is mined or unless the support system which helps maintain the confinement is overloaded. The existence of favourably oriented joint planes or structures may also play an important role. During this process, it is important to recognize that the proposed conjugate shear zones, daylight at the shoulder and not in the back itself which continued to appear intact for the life of the project.



a **b** **c**

Figure 23: Alternative model for the fracture pattern progression around the development

As shown in figure 23, the suggested alternative model is based on (a) initiation at the shoulder (b) propagation of inclined conjugate zones and (c) coalescence. During the course of the project, this transition began from the initial development stage shown in (a), though early progression of the adjacent primary stope (b) and to the final stress state following the 1.7Mn event.

According to this mechanism the back may continue to look in really good shape whereas the conditions of shoulders will indicate what is really happening. Physical observations underground clearly support the results. The conceptual model emphasizes the inter-relation between support elements in the back and support elements of different length in the back.

It is interesting to note that the 'dog-eared' profile formed as a result of this mechanism (figure 23c) resembles the borehole breakouts photographed in figure 6 except at a different scale. In both cases, the breakout is driven by the differential stress: σ_{hmax} - σ_{hmin} for the vertically oriented borehole, and σ_{hmax} - σ_v for the development excavations; the latter being enhanced due to the fact that mining above the level has now cut-off the vertical stress component as shown in figure 4. Hence the dog-ear profile may be considerably more likely for the excavation than for the borehole and may be further affected firstly by the relatively flat back of the excavation, and the stiff primary support in the back. In addition rock jointing will pay a more major role at the scale of the excavation. Slip on pre-existing joint sets in addition to any new crack growth will play a major role in the mechanism.

10 CONCLUSION

Information gained in this project provided useful information to VALE Creighton Mine operations with regards to effects of primary-secondary mining and whether it could be considered elsewhere. The project was also beneficial in the understanding of the mechanism between the stiff and dynamic ground support system currently being used at the mine.

The rebar and MCB in the 6770 Oresill both loaded up significantly during mining, most notably during Blast 5 and the subsequent 1.7Mn seismic event. While the resin rebar exhibited yield of the steel the MCB remained below steel yield and after the 1.7Mn event, displayed an irregular load history which is indicative of "ploughing". This information, although limited, provided a good understanding to management and to operators who are currently installing the rebar and MCB as a first pass system at current or anticipated high stress areas. The first pass system is continually being monitored, although other than to say that it is extremely successful, follow-up information remains outside the scope of this report.

Extensometers and instrumented cables installed in the back at the Oresill drift indicate very small amounts (approx 0.8mm) of movement/load. The movement recorded is > 3.2m into the back. These results suggest that the deformation pattern in the back and shoulders does not simply result from concentric "extensile" fracturing but may involve deeper crack propagation along planes of high shear stress. The limited dataset from this experiment cannot definitively prove this mechanism, although Creighton Mine is currently monitoring similarly elsewhere for anticipated high stress conditions.

Borehole Pressure Cells installed into the secondary pillar from the overcut display reasonable changes in stress during the mining sequence. Following the primary stope crown blast a stress increase of 20MPa was recorded through the pillar with a corresponding -60MPa reduction in the longitudinal direction. This +80MPa increase in differential stress suggests that the pillar has not attained peak load (i.e. failed), an important consideration for stand-up time and break-out of a primary panel.

The instrumentation project ended with the onset of the secondary pillar mining, although the ultimate success of the project pended results of the project as part of the stope reconciliation process. A 3D cavity monitor survey reveals the mining geometry of the primary stope in figure 24. Figure 25 shows completion of the project following mining of the secondary panel, 4408 (note that mined-out geometry above the current mining horizon are not shown).

Economics of course, plays a big part in the success of any project. Ore recovery is critical to the overall picture, of which dilution plays a large role. In the case of the primary stope, there is no fill dilution; recoveries then are the same as for any first mined panel. Looking at dilution results from the secondary panel then, twice the normal sand dilution could be expected as there will be fill on both sides. Computing the combined dilution of the secondary and primary stope and looking at an average, it was discovered that the result was 2.5% higher than average for the area, but only 1.2% higher than for the neighboring 4448 Stope conciliation result.

In subsequent analysis, an important consideration is the fact that 25% more dilution occurred blasting up against the 4368 primary stope than occurred against the previously mined 4448 panel, and it was 20:1 vs 25:1 fill. Some of the dilution costs may be absorbed by the savings generated from not having to hoist rock, as the body of 4408 was used as a rock stope, but does not fully offset the cost of sand dilution or monitoring expense. A question needs to be raised as to why did this occur and is addressed the closing comments of Chapter 11.

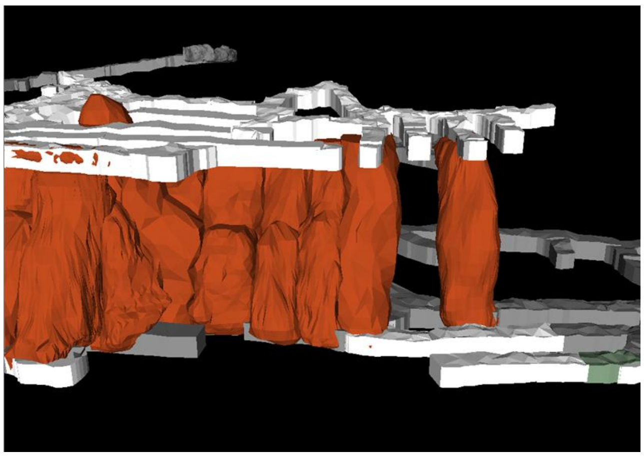


Figure 24: 4368 Primary Stope Mined

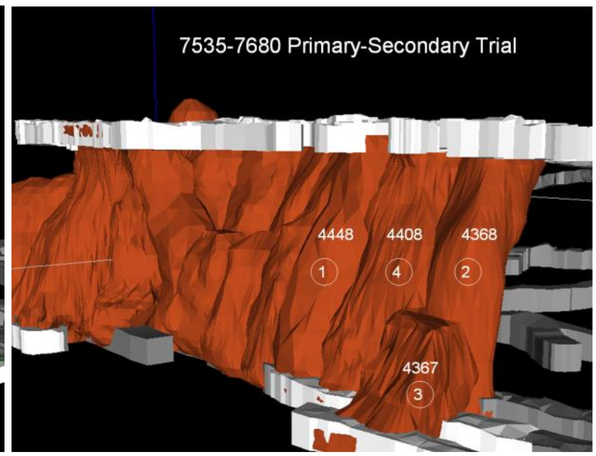


Figure 25: 4408 Secondary Stope Mined

11 PATH FORWARD

Despite the dilution results experienced, the project was very successful. Prior to setting up another primary-secondary project, the Creighton operation will investigate pre-emptive blast control measures to minimize sand dilution. It is believed that further enhancements can be made with tighter controls on the placement of explosives and/or optimized borehole diameters when mining a secondary panel. Locations will need to continue to be carefully investigated for suitability (i.e. secondary access availability, massive ore zones without brittle rock inclusions). Further monitoring will be a part of such projects.