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Management of production drift convergence and redevelopment

C Kamp *New Gold Inc., Canada*

Abstract

New Afton Mine is a block caving operation, located approximately 10 kilometres outside of Kamloops and 350 kilometres northeast of Vancouver in British Columbia. The New Afton orebody has a unique combination of geometric and geotechnical conditions, including a long and narrow footprint which is highly faulted and hence comprises large areas of poor ground, all of which is subject to a relatively high major horizontal principal stress. The initial deformations (convergence) experienced on the production level (extraction level) of the Lift 1 West Cave proved relatively manageable; however, as mining moved eastward towards the Lift 1 East Cave, which comprised significantly poorer rock mass quality, deformation rates increased causing substantial damage and subsequent repair of the footprint.

Block caving in a poor rock mass subject to high cave induced stress changes typically experience large plastic deformations which manifest as drive convergence and in some cases complete drive closure. Such conditions require comprehensive extraction drive and drawpoint redevelopment (rehabilitation), which consequently increases operating costs and constraints production. A conceptual model of convergence and comprehensive ground control rehabilitation strategy for existing drawpoints and extraction drives has been implemented at the New Afton Mine with the aim of managing rock mass damage and maintaining drawpoint integrity until mining is exhausted. A review of ground support and rehabilitation methods along with the conceptual convergence model are discussed. An example case of a drawpoint and associated extraction drive area that was successfully recovered following high convergence is presented.

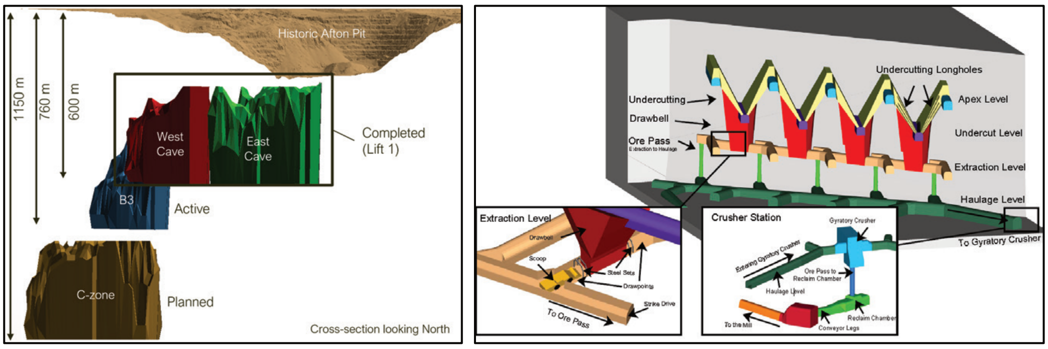
Keywords: *convergence, ground support, rehabilitation, caving*

1 Introduction to New Afton

New Afton is a copper-gold orebody situated on the Stk'emlupsemc te Secwépemc territory, within the unceded traditional lands of the Secwépemc nation near Kamloops, British Columbia, Canada. New Gold Inc. Construction and development of the New Afton block cave mine began in 2007 and initiated production in July 2012, following the first drawbell blast in September 2011 in the Lift 1, West Cave. The Lift 1 caving operation lies below the historic Afton open pit mine, which operated from 1977 until 1997. The site also includes an inactive dewatered open pit and other historical surface facilities.

In 2021 and 2022, New Afton completed its first two Block Caves on Lift 1, the West and East Caves, which mined over 24.5 MT and 23.7 MT respectively. Currently, New Afton successfully initiated and is monitoring steady state caving of a third cave (B3) beginning in January 2022 with 8.8 MT (probable tonnes). Production involves milling over 8,000 tpd stemming from both the B3 Cave and a recovery level located below the East Cave. Decline drifts are currently being developed down to a fourth cave (C-Zone), which comprises 29.5 MT (probable tonnes) (Figure 1).

This paper focuses on the rehabilitation areas of the completed East Cave.



(a) (b)

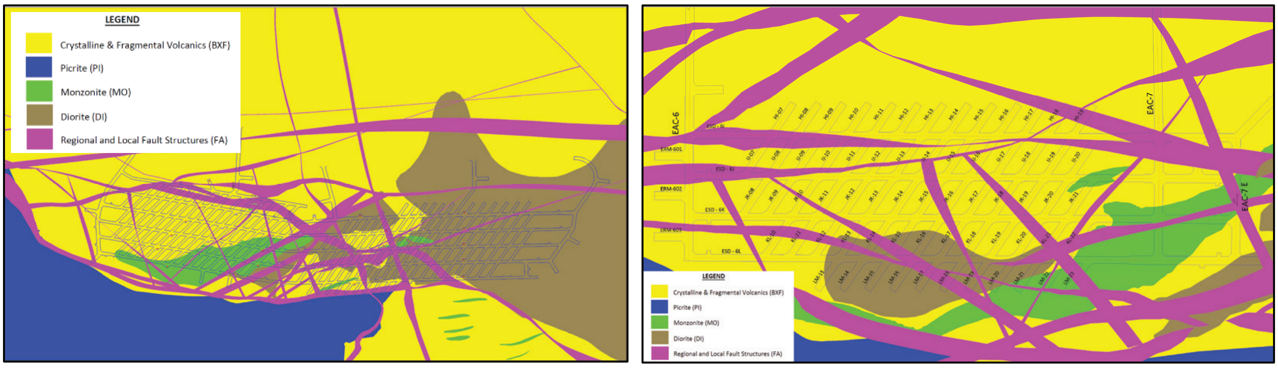
Figure 1 **(a) Cross-section view (mine grid north) of New Afton caves; (b) Isometric view of apex, undercut, extraction and material handling levels**

New Afton Lift 1 caves (Figure 1a) adopted an El Teniente extraction level layout and were the first caving operation to implement an apex level above the undercut level. However, for the B3 Cave, the apex level was only utilised until the expected critical hydraulic radius (HRcr) was reached and steady state caving was assured, the undercut was then transitioned to apex-less undercutting.

2 Geology and rock mass conditions

The principal host lithologies for the mineralisation on the production levels are crystalline and polymictic fragmental rocks and monomictic intrusive breccias, grouped together as a unit termed BXF, which primarily makes up the West, B3 and C-Zone Caves. In the eastern half of the deposit, specifically for the East Cave, the BXF is intruded by a diorite sill (DI). These units are bounded on the east by younger basalts and sedimentary rocks and bounded by an ultramafic picritic flow (PI) to the south. Monzonite (MO) bodies encompass both the BXF and DI and is interpreted to be a causative intrusive phase for mineralisation.

Geological mapping of the underground workings is conducted for every tunnel advance. Mapping in conjunction with extensive geotechnical core logging provide clear evidence of a highly jointed rock mass with rock mass quality negatively influenced by faulting and alteration. Plan view lithology and structural maps in Figure 2 illustrate the geotechnical complexity of lithological domains and faults. Specifically, the major faults and structurally controlled areas associated with the BXF and diorite contact and propylitic alteration result in pervasive hematite and chlorite which are found in the East Cave (Figure 3). These areas have a rock mass rating of RMR89′ =<37 (lower quartile), due to the low rock strength, weak joint conditions and low rock quality designation (RQD), and hence bolting the tunnel face prior to charging may be required to prevent the face from sloughing during the drilling cycle and/or after scaling.



(a) (b)

Figure 2 **(a) Fault and lithology for Lift 1 (West and East Caves in plan view, mine grid north) located 600 m below surface with 15 × 27 m and 18 × 27 m drawpoint pillar centre to centre spacings; (b) B3 Cave, located 760 m below surface with 16.5 × 27 m drawpoint pillar centre to centre spacing**

(a) (b)

Figure 3 **(a) Example of alteration effects on the BXF–diorite contact resulting in RMR<37, and the rock mass from the face sloughing after scaling; (b) Extraction drive undergoing rehabilitation due to high levels of convergence in similar faulted and altered rock mass**

Classification of the rock mass is determined using several methods at New Afton, utilising both core logging and face mapping. The Bieniawski (1989) classification system (RMR89), indicates a median rock mass rating of 58–68 with a median RQD of 63–78 and median uniaxial compression (UCS) within the orebody of 60–71 MPa, excluding faults. Face mapping of the extraction levels provides an RMR89 median range of 45–52 (Table 1), which is less than the orebody values (obtained by core logging), concluding the orebody is of better rock mass than the extraction level rating due to spatial location of faulting and alteration at the extraction level elevation.

Table 1 **RMR’89 of the mining resource (orebody) block estimated from core logging, with face mapping of the extraction level (in brackets)**

Parameter		Orebody (extraction level)		
		West cave	**East cave**	**B3 cave**
RQD	Median	75	63	78
(%)	25th percentile	60	43	65
	75th percentile	87	78	89
	Median	66 (50)	58 (45)	68 (52)
RMR’89	25th percentile	58 (45)	47 (37)	60 (47)
	75th percentile	72 (55)	66 (50)	74 (56)

2.1 In situ and induced stress

Stress measurements were undertaken at New Afton using overcoring techniques, namely CSIRO HI and HID cells along with Sigra Pty, all of which reveal a relatively high horizontal stress environment (Haveman 2021). Where the intermediate horizontal stress magnitude is estimated as a function of the major principal stress magnitude assuming an SH/Sh ratio of 1.7 (Figure 4).

$$Sigma\ 1\ (SH) = 12.8 + 0.029 * depth$$

$$Sigma\ 2\ (Sh) = 7.5 + 0.017 * depth$$

$$Vertical\ (Sv) = 0.0265 * depth$$

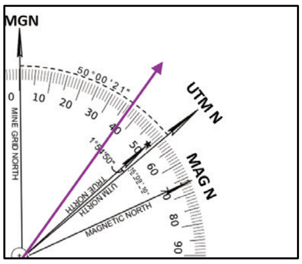


Figure 4 Sigma 1 (SH) relative to UTM and mine grid north (MGN)

Numerical modelling and observations underground indicate half drawbells can reduce the risk to perimeter strikedrives during the production phase of caving (Figure 5), and also increase the hydraulic radius potential to promote the initialisation of caving for a narrow footprint.

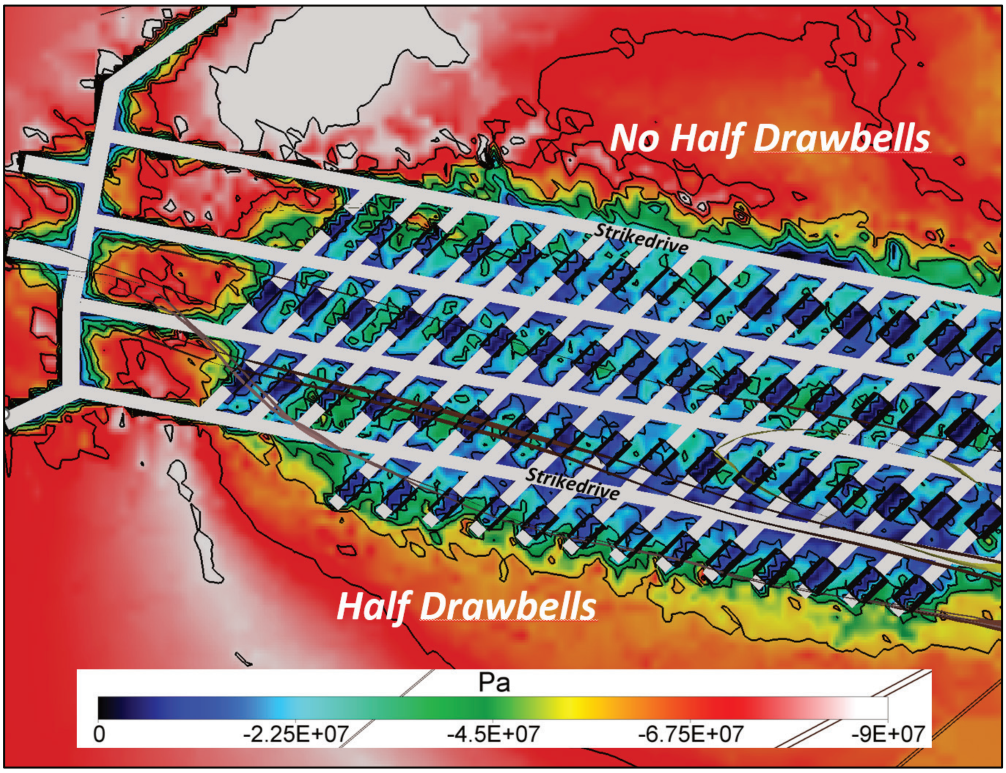


Figure 5 Benefits of adding width by adding half drawbells to widen the footprint and 'deepen' the stress away from the cave perimeter (Beck 2017)

2.2 Extraction level pillar classification

Core logging provides sufficient data from which an initial understanding of the rock mass response to caving can be assessed. However, face mapping and ongoing structural mapping of the tunnels, primarily from the extraction drives and drawpoints is fundamental to extraction level pillar and ground support designs. In addition to conventional rock mass rating (RMR) or Q-Index rock mass quality methods, New Afton has also adopted a simple rock mass rating system for pillar classification, which comprises simply 'good', 'poor' or 'very poor' classification, based on the RMR89 values and presence of major structure and alteration. This classification is initially undertaken using core logging data, structural models and alteration models, and is subsequently refined using the face mapping data acquired from the apex, undercut and extraction level drives, prior to drawpoint development. The results provide a pillar classification summary for the extraction level (refer to Figure 6 and Table 2) which informs the selection of the appropriate ground support class as well as considerations for blasting to avoid excessive overbreak.

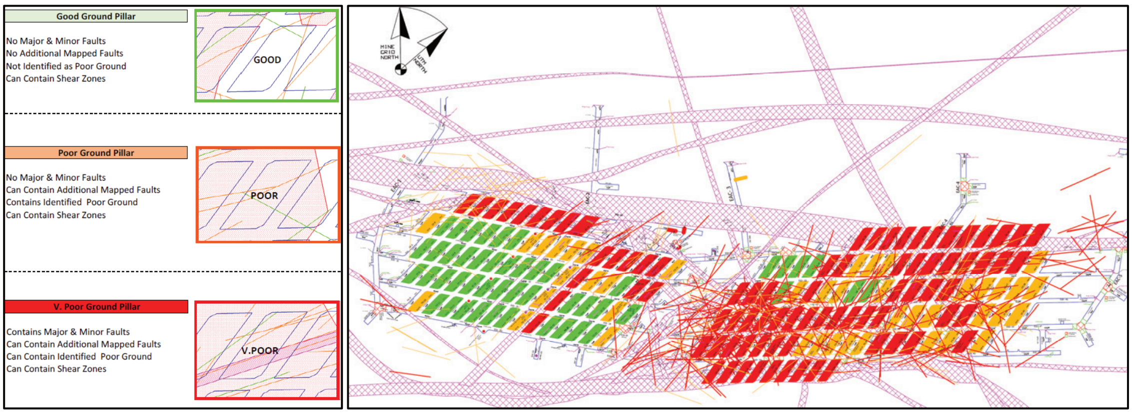


Figure 6 Example of simple rock mass rating for pillar classification. Showing Lift 1 (West and East Cave)

Table 2 Summary of New Afton Caves using simple rock mass rating for pillar classification

Parameter		West Cave	East Cave
Pillar classification	Good	54%	7%
	Poor	20%	28%
	Very poor	26%	65%

3 Ground support

New Afton's ground support designs for the extraction level have significantly changed from those proposed in the original feasibility study (FS). The West Cave was the first Cave at New Afton and utilised the support standards proposed in the FS for the initial development. Whilst much of this original support system did not require rehabilitation, sequential changes over the years were made to the designs (refer to Figures 7 and 8, along with Table 3), primarily based on face mapping and a re-interpretation of the structural model, discoveries of weaker and altered ground conditions in the East Cave, and experience gained from the onset of localised convergence areas in the West Cave.

From 2012 to 2016, the support classes were incrementally upgraded to account for the significant increase in poorer ground conditions during the development of the East Cave. The 2016 revision required a considerable increase in long anchor support and consequently necessitated an increase in ground support, labour, as well as additional equipment, such as self-contained cablebolting rigs. Findings from the simple rock mass rating system for pillar classification in Section 2 are then used to make adjustments to support standards spacings and locations, for example, Figure 8 shows cablebolting between the drawpoint brow locations, this is specific to the 'very poor' pillar classification.

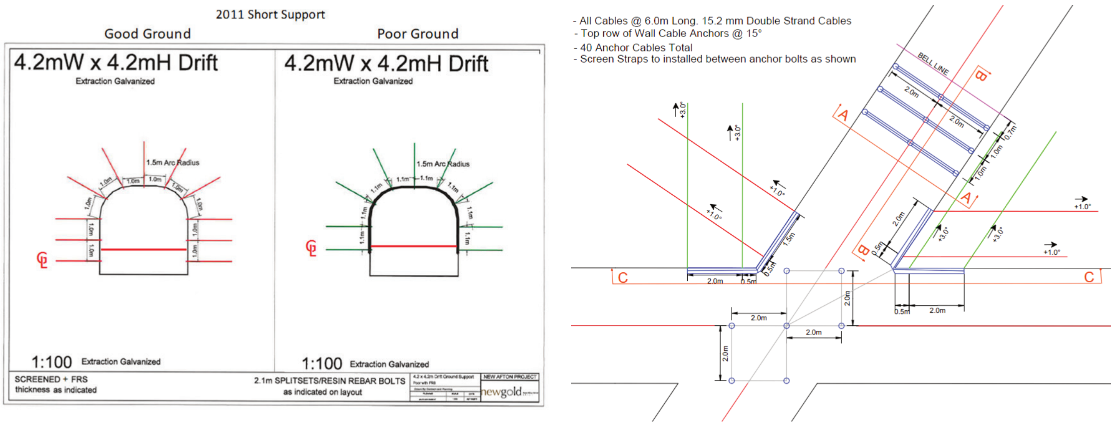
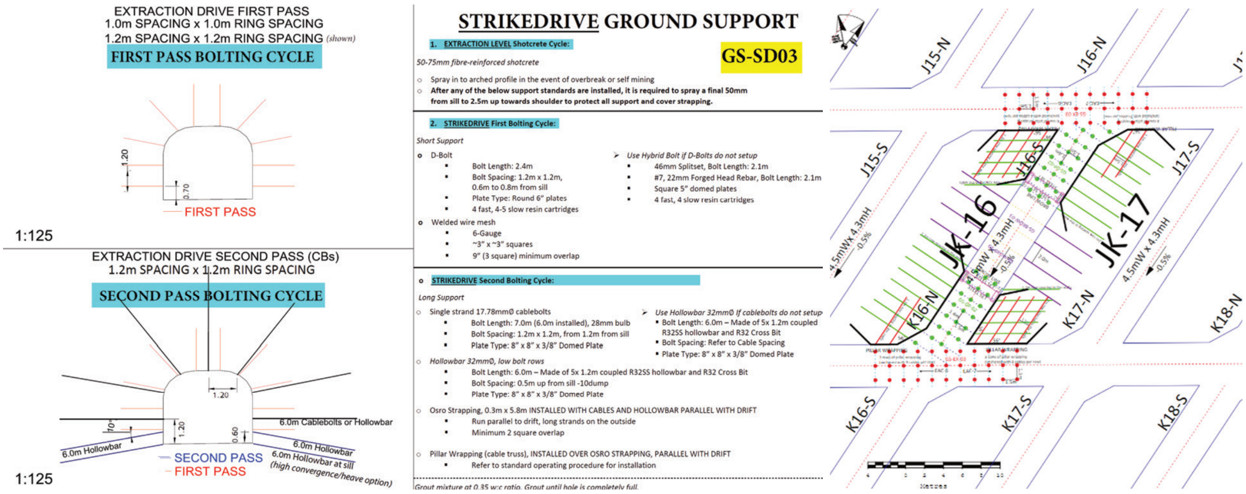


Figure 7 Feasibility ground support for extraction strike drives and drawpoints



STRIKEDRIVE GROUND SUPPORT

GS-SD03

1. EXTRACTION LEVEL Shotcrete Cycle:

50-75mm fibre-reinforced shotcrete

- Spray in to arched profile in the event of overbreak or self mining
- **After any of the below support standards are installed, it is required to spray a final 50mm from sill to 2.5m up towards shoulder to protect all support and cover strapping.**

2. STRIKEDRIVE First Bolting Cycle:

Short Support

- D-Bolt
  - Bolt Length: 2.4m
  - Bolt Spacing: 1.2m x 1.2m, 0.6m to 0.8m from sill
  - Plate Type: Round 6" plates
  - 4 fast, 4-5 slow resin cartridges
- *Use Hybrid Bolt if D-Bolts do not setup*
  - 46mm Splitset, Bolt Length: 2.1m
  - #7, 22mm Forged Head Rebar, Bolt Length: 2.1m
  - Square 5" domed plates
  - 4 fast, 4 slow resin cartridges
- Welded wire mesh
  - 6-Gauge
  - ~3" x ~3" squares
  - 9" (3 square) minimum overlap

STRIKEDRIVE Second Bolting Cycle:

Long Support

- Single strand 17.78mmØ cablebolts
  - Bolt Length: 7.0m (6.0m installed), 28mm bulb
  - Bolt Spacing: 1.2m x 1.2m, from 1.2m from sill
  - Plate Type: 8" x 8" x 3/8" Domed Plate
- *Use Hollowbar 32mmØ If cablebolts do not setup*
  - Bolt Length: 6.0m – Made of 5x 1.2m coupled R32SS hollowbar and R32 Cross Bit
  - Bolt Spacing: Refer to Cable Spacing
  - Plate Type: 8" x 8" x 3/8" Domed Plate
- *Hollowbar 32mmØ, low bolt rows*
  - Bolt Length: 6.0m – Made of 5x 1.2m coupled R32SS hollowbar and R32 Cross Bit
  - Bolt Spacing: 0.5m up from sill -10dump
  - Plate Type: 8" x 8" x 3/8" Domed Plate
- Osro Strapping, 0.3m x 5.8m INSTALLED WITH CABLES AND HOLLOWBAR PARALLEL WITH DRIFT
  - Run parallel to drift, long strands on the outside
  - Minimum 2 square overlap
- Pillar Wrapping (cable truss), INSTALLED OVER OSRO STRAPPING, PARALLEL WITH DRIFT
  - Refer to standard operating procedure for installation

Grout mixture at 0.35 w:c ratio. Grout until hole is completely full.

Figure 8 2016+ ground support for extraction strikedrives and drawpoints

Table 3 Transition of initial extraction level ground support from 2011 to 2016 onwards

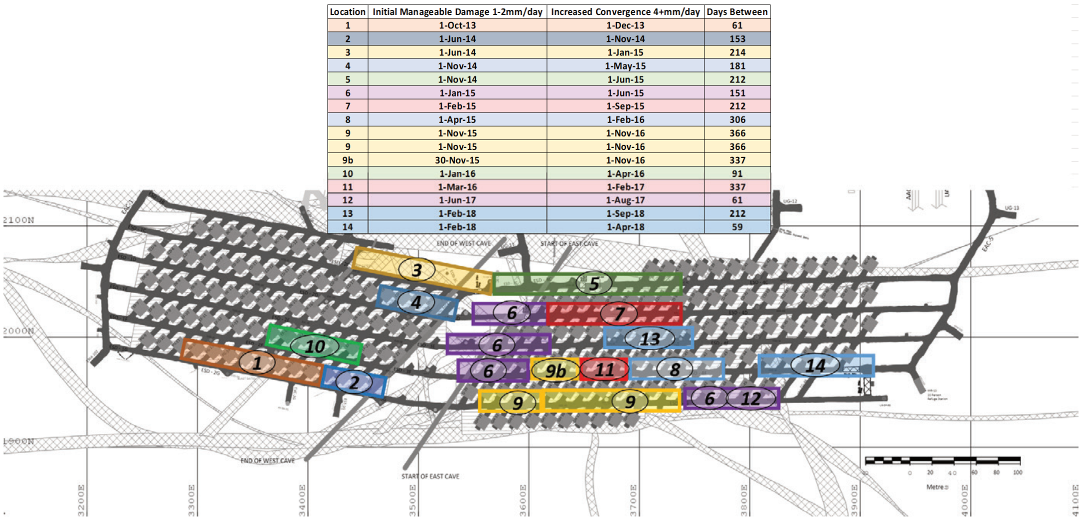
Extraction level support	Feasibility (FS)	2016+
Shotcrete	50–75 mm, fibre-reinforced	50–75 mm, fibre-reinforced, with second pass spray from sill to shoulder of 30–50 mm
Screen	Weld wire, 6-gauge	Weld wire, 6-gauge
Short support	Splitsets, galvanised, 46 mm, 2.1 m long	Rebar/D-Bolts, #7 22 mm, 2.4 m long or, Hybrid Bolts, 46 mm Splitsets with #7 22 mm forged head rebar resin spun inside, 2.1 m long or MD or MDX Bolt, 47 mm, 2.4 m long
Long support	Cablebolts (CB), bulbed, 15.24 mm, 6.0 m long	Cablebolts, bulbed, 17.8 mm, 6.0–9.0 m long or Hollowbar (self-drilling anchors), R32SS, coupled to 6.0 m long or as needed
Strapping	0-gauge weld wire strapping tied in with CB	Osro strapping tied in with CB
Pillar wrapping (cable bolt sling)	N/A	Three rows of 15.8 mm twin cable slings pinned with cable bolts used to support the drawpoint pillars, placed over the Osro strapping.
Bolt spacing	Short support: 1.0–1.1 m Long support: selective areas only at 2.0 × 2.0 m	Short support: 1.0–1.2 m Long support: entire extraction level at 1.0–1.5 m

4 Convergence

Convergence at the New Afton Mine has been experienced during the mining of West Cave following breakthrough to surface. Since then, the mine has successfully rehabilitated many of these areas to achieve production.

When an area is identified for rehabilitation, the geotechnical department conducts an audit of the area and provides a geotechnical ground control (GGC) sheet with the rehabilitation plan. To date, over 1,700 GGC documents have been issued and successfully completed since March 2012, consisting of over 2,500 m of notable rehabilitation ranging from very minor increases in ground support, to full redevelopment of a fully converged (no longer accessible due to rock mass deformation) extraction drive or tunnel (Figure 9). From this, experience has been gained on what observations are related to convergence rates and what methods of rehabilitation should be chosen.

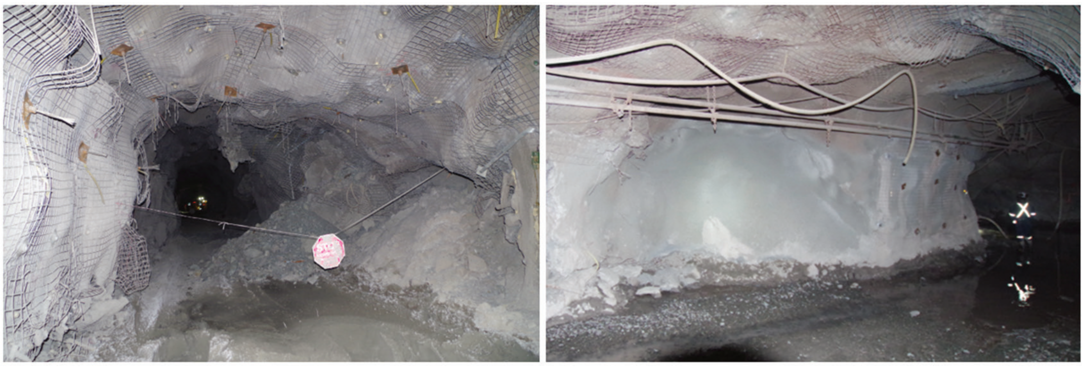
The onset of convergence can be caused by geology or mining related activities (not discussed in this paper) and initially begins as horizontal convergence at a manageable rate of movement. In some cases, rate will increase with time, vertical convergence will occur, and rates can accelerate to a less manageable rate of movement (Figure 9).



Location	Initial Manageable Damage 1-2mm/day	Increased Convergence 4+mm/day	Days Between
1	1-Oct-13	1-Dec-13	61
2	1-Jun-14	1-Nov-14	153
3	1-Jun-14	1-Jan-15	214
4	1-Nov-14	1-May-15	181
5	1-Nov-14	1-Jun-15	212
6	1-Jan-15	1-Jun-15	151
7	1-Feb-15	1-Sep-15	212
8	1-Apr-15	1-Feb-16	306
9	1-Nov-15	1-Nov-16	366
9	1-Nov-15	1-Nov-16	366
9b	30-Nov-15	1-Nov-16	337
10	1-Jan-16	1-Apr-16	91
11	1-Mar-16	1-Feb-17	337
12	1-Jun-17	1-Aug-17	61
13	1-Feb-18	1-Sep-18	212
14	1-Feb-18	1-Apr-18	59

Figure 9 Lift 1 – West and East Caves shown with areas of convergence occurrences from 2013 to 2018, showing days between initial onset of minor convergence and increased convergence

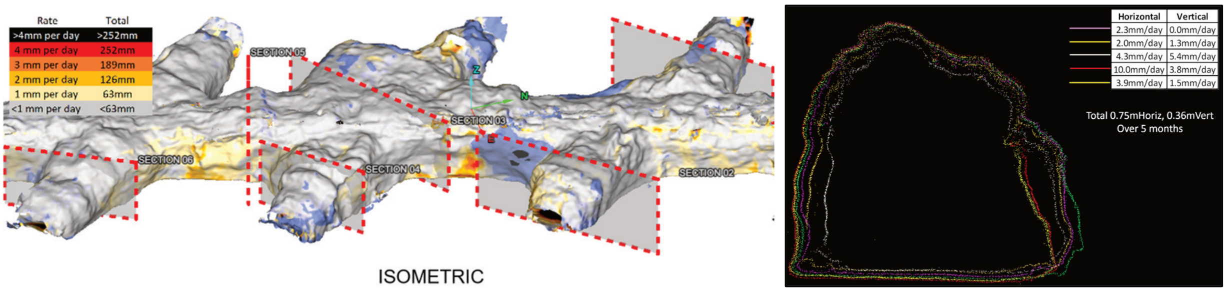
During the rehabilitation process, significant coordinated planning between the engineers and mine Operations is required. Routine inspections conducted several times per week or as needed are completed to review the areas of convergence. At this time, observations of ground support performance, bogging (mucking) rates, measurements of convergence and extensometer data review are completed. This information is then compiled to communicate a feasible geotechnical short-term and long-term rehabilitation plan for the area; involving a recommendation of ground redevelopment (if needed), and a ground support and instrumentation monitoring plan. In extreme cases, where the convergence is unable to be maintained, drifts are temporarily closed or filled with concrete until a dedicated rehabilitation project can be commenced (Figure 10).



(a) (b)

Figure 10 View of two separate areas of extraction drive with high convergence rates (>4 mm/day). (a) A drawpoint without concrete, resulting in extraction drive deformation; (b) Filled with oversize material and concrete resulting in a more stable strikedrive

Convergence monitoring data are obtained routinely via visual damage mapping, from extensometer data, and with a handheld laser scanner, which produce 3D tunnel scans (point clouds and triangulations). These scans are compared to previously obtained scans, allowing visual comparative heatmaps and cross sections to be created, providing interpretation of convergence rate, tunnel profile (Figure 11) and ground support performance.



(a) (b)

Figure 11 (a) Laser scanning to create triangulations to compare with previous scans for visualisation of convergence rates, seen in isometric view; (b) Cross-section example from a different area than 12(a), of several scans used to understand convergence changeover time. Scans are also used to understand ground support performance

Draw strategies to ensure continuous mucking is being done at the local area of convergence and around the area are discussed to potentially reduce convergence. Other operations have also observed decreases in convergence once mucking strategies are employed (Febrian 2004; Millán & Quezada 2012; Sahupala & Srikant 2007a, b).

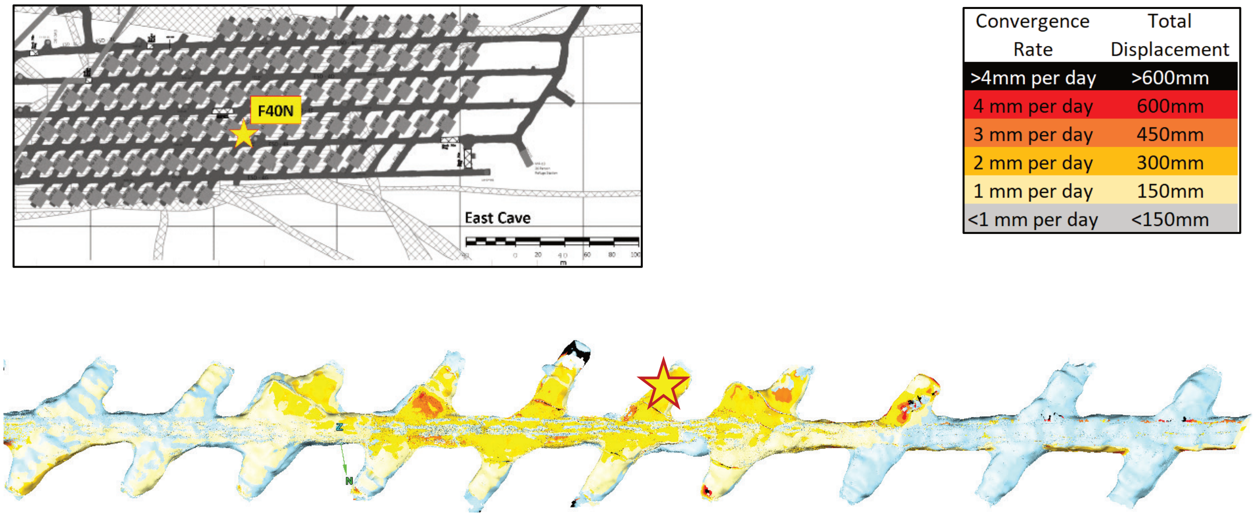
New Afton monitors convergence rate (mm/day) rather than cumulative convergence, from experience setting action response plans to convergence rate is more practical to manage than cumulative convergence, as there are multiple factors that can vary such as induced stress, undercutting, rock mass quality etc. that can cause tunnels to be unstable at different cumulative convergence values. However, cumulative convergence is used to understand ground support yield and ultimate capacity, resulting in decisions to replace ground support as required. The approach to convergence management based on mm/day is discussed in Section 6.

5 Case study

5.1 Introduction

The provided case study is a 40 m extraction drive and drawpoint (F40N) located in the East Cave that was rehabilitated from fully converged due to an areas of ongoing convergence, exceeding 4 mm/day (Figures 12 and 13). A sequential redevelopment, ground support installation and drawpoint re-initiation was successfully employed, allowing mining of the drawpoint until exhaustion with manageable convergence rates of <1 mm/day.

In some rehabilitation cases, additional ground support (confinement based support) beyond standard bolting is required to manage convergence. Confinement based support systems are designed to be ductile, where flexibility follows large ground deformation, while also confining the rock mass excavation and associated areas of convergence This is achieved at New Afton using arching or strapping techniques (Figure 16). In addition, the timing of ground support installation is important to align with ground support reaction observations, which is managed through planning schedules (Figure 14) and routine convergence measurements. This case study utilises confinement based support to provide additional confinement of the rock mass, not all cases successfully rehabbed at New Afton required these additional systems.



Convergence Rate	Total Displacement
>4mm per day	>600mm
4 mm per day	600mm
3 mm per day	450mm
2 mm per day	300mm
1 mm per day	150mm
<1 mm per day	<150mm

Figure 12 Scan of strikedrive in plan view, showing area experiencing convergence with F40N drawpoint

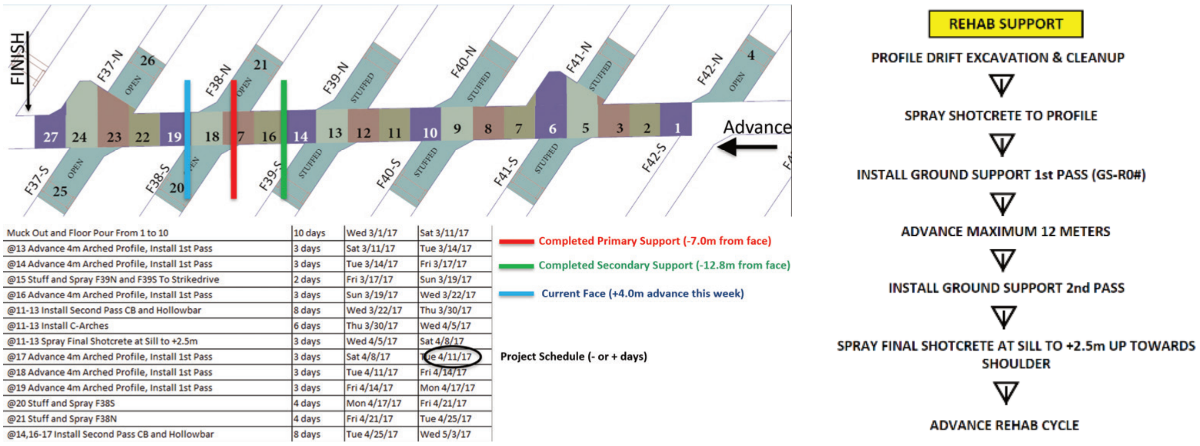
5.2 Planning

Initial convergence at F40N drawpoint was routinely scanned and notably observed at the end 2015 with increasing convergence to 1–2 mm/day about 250 days later, 2–4 mm/day about 340 cumulative days and then >4 mm/day at 360 days, resulting in difficulty to access the drawpoint due to narrowing of the drawpoint (Figure 13). The drawpoint was then concreted closed (Figure 10b) to reduce further damage to the strikedrive, while a rehabilitation execution plan could be developed.

(a) (b)

Figure 13 (a) Picture of F40N exceeding 4 mm/day; (b) Triangulation and point cloud cross-section overlaid to illustrate convergence over time (scale as noted in Figure 12)

An execution plan was created with the purpose to first rehabilitate the extraction drive and monitor through convergence scanning and damage mapping. If the extraction drive would remain stable, then planned rehabilitation into the drawpoint would occur. A project timeline was created using historical rehabilitation rates with 4.0 m advances (Figure 14a) and strategic short and long support installations (Figure 14b) were chosen based on experience from ground-response observations and convergence measurements. During the rehabilitation advance of the extraction drive, if a drawpoint was not concreted prior it would be concreted once encountered.



Muck Out and Floor Pour From 1 to 10	10 days	Wed 3/1/17	Sat 3/11/17
@13 Advance 4m Arched Profile, Install 1st Pass	3 days	Sat 3/11/17	Tue 3/14/17
@14 Advance 4m Arched Profile, Install 1st Pass	3 days	Tue 3/14/17	Fri 3/17/17
@15 Stuff and Spray F39N and F39S To Strikedrive	2 days	Fri 3/17/17	Sun 3/19/17
@16 Advance 4m Arched Profile, Install 1st Pass	3 days	Sun 3/19/17	Wed 3/22/17
@11-13 Install Second Pass CB and Hollowbar	8 days	Wed 3/22/17	Thu 3/30/17
@11-13 Install C-Arches	6 days	Thu 3/30/17	Wed 4/5/17
@11-13 Spray Final Shotcrete at Sill to +2.5m	3 days	Wed 4/5/17	Sat 4/8/17
@17 Advance 4m Arched Profile, Install 1st Pass	3 days	Sat 4/8/17	Tue 4/11/17
@18 Advance 4m Arched Profile, Install 1st Pass	3 days	Tue 4/11/17	Fri 4/14/17
@19 Advance 4m Arched Profile, Install 1st Pass	3 days	Fri 4/14/17	Mon 4/17/17
@20 Stuff and Spray F38S	4 days	Mon 4/17/17	Fri 4/21/17
@21 Stuff and Spray F38N	4 days	Fri 4/21/17	Tue 4/25/17
@14,16-17 Install Second Pass CB and Hollowbar	8 days	Tue 4/25/17	Wed 5/3/17

(a) (b)

Figure 14 (a) Example of planning schedule; (b) General rehabilitation sequence created from experience from ground-response observations and convergence measurements

5.3 Rehabilitation methods

Redevelopment of the drift was completed by pre-drilling perimeter holes and advancing with a rock breaker to avoid additional damage to the profile and to avoid overbreak. When this method did not work, controlled blasting was used. Once an initial ground support was applied, the damaged bolts from the re-excavated tunnel needed to be removed to allow for a stable profile during the support cycle (Figure 15).

(a) (b)

Figure 15 (a) Drilling the redevelopment face; (b) Example of old/damaged bolts from redevelopment, requiring removal prior to new support

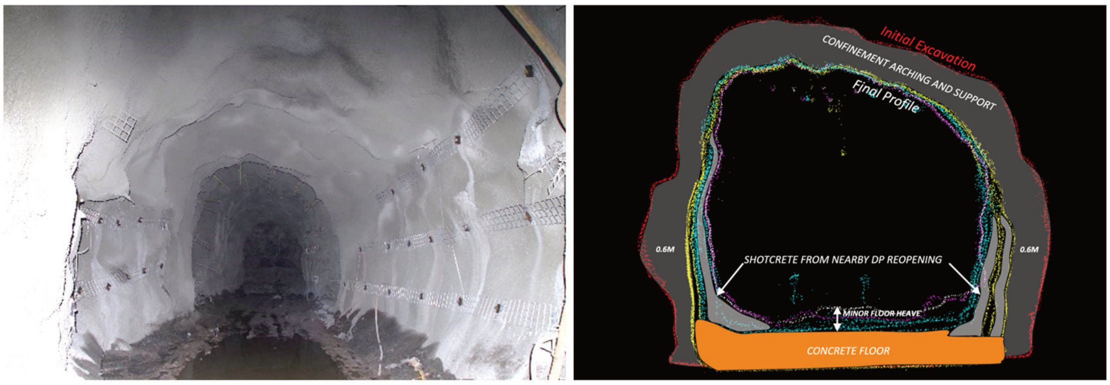
First pass support was then installed similar to Figure 8, with a tight bolt spacing typically using hybrid bolts as the bolter drillholes would collapse during rebar bolt installations and not allowing resin cartridges to be injected or the rebar bolt to be advanced. In some cases, Hollowbar (SDA) were used as replacements for short bolting.

Second pass (long) support system is a similar concept to Figure 8. However, for this example the cable bolt stick out (tails) were left at +1 m outside the collar and not cut after the plate and tension process. This was done to leave room to anchor a chosen confinement based support method to the rock mass. Confinement based support can be achieved through C-Arches (rebar and shotcrete arching, then bolted over with screen and bolts), Osro strapping and cable bolt slings, or 4-bar lattice arches, all of which are ductile and allow for yielding of the rock mass.

(a) (b) (c)

Figure 16 Examples of confinement based support. (a) C-Arches; (b) Cable bolt slings and Osro strapping; (c) Lattice arches

For this example, C-Arches and strapping methods were used to successfully re-develop the extraction drive, and lattice arches and strapping were used for the drawpoint. Both methods also involved excavating the floor, allowing the support systems to be poured in place with concrete to provide a better footing. Planned over excavation of the tunnels was required to allow for these support systems, routine 3D scans were utilised to monitor the progress and support the QA/QC construction process, the final support thickness for the extraction drive was about 0.6–0.7 m (Figure 17).



(a) (b)

Figure 17 (a) Completed strikedrive rehabilitation; (b) Cross-section using point cloud scans to determine support thickness

Once the 40 m of extraction drive was fully rehabilitated, the area was monitored for convergence, and it was found that the rates had decreased. The strategy then involved re-opening F40N drawpoint and if successful, every second drawpoint, subsequently continuing to monitor and finally opening the drawpoints in-between, as this strategy was successful for other areas in the East Cave.

Prior to the redevelopment into F40N, investigation drilling was done to confirm if the centreline of the drawpoint is within expectations, as the ground has experienced significant deformation, the survey lines may no longer be accurate. Previous and current scans were used to setup the investigation drilling and resultant redevelopment plan.

Advances into the drawpoint are typically done in 2.0–4.0 m rounds, depending on the conditions. Once the redevelopment of a drawpoint has started, there is risk for convergence to accelerate again in the area, requiring a constant rehabilitation process, hence planning is essential. Redevelopment is continued until the original steelsets are found, then second pass long support is installed. After the long support is installed, investigation drilling is completed in front of the steelsets near the brow to understand what pillar remains between the rehabilitated drawpoint and the drawbell. After this, the old steelsets are removed and new steelsets are installed. In some cases, after the original steelsets are removed and the ore column is exposed, a high level of compaction to the ore column is typically observed within the drawpoint, making the draw challenging to re-establish (Figure 18). Methods to re-initiate draw typically include water sprayers and rockbreaker and in some cases blasting.

(a) (b)

Figure 18 (a) Compaction beyond the brow observed after redevelopment of a fully converged drawpoint, the dashed lines represent converged walls within the drawpoint (originally 4.2 m wide); (b) Water sprayer used to assist with loosening the compaction to re-establish the flow of the ore column

Once the ore column flow resumes, a ramp up mucking approach is taken, with mucking adjacent and nearby drawpoints to in an effort to support the re-established flow of the drawpoint. At this time after the drawpoint has re-established the flow of the ore column and 'connected to the cave' again, the convergence rates should diminish once the drawpoint is being regularly mucked. If a drawpoint is re-established after convergence rehabilitation and not production mucked, the area will likely experience high rates of convergence again.

The life of F40N drawpoint in terms of mined tonnes versus drawpoint and extraction drive convergence rate is illustrated in Figure 19. It was observed that after the initial drawbell blast in 2015, convergence occurred in the extraction drive and at F40N drawpoint area. Convergence increased over time during production until the drawpoint was no longer able to be mucked at only 9% drawn from the mine plan. The rehabilitation process did not commence immediately, but once initiated progressed at an average rate of about 3–4 m/week (full support systems installed). After extraction drive rehabilitation was completed, convergence was minimal, however during rehabilitation of the drawpoint, an initial increase in convergence was observed in both the extraction drive and at F40N drawpoint. This trend continued until the F40N compacted ore column was re-mobilised by water sprayers and mucking allowing F40N draw to be 'connected to the cave', after which a decrease in convergence rates was observed allowing production to commence. As closure approached (2020), F40N tonnage decreased, resulting in another onset of elevated convergence rates. The data ends with the drift being closed from production.

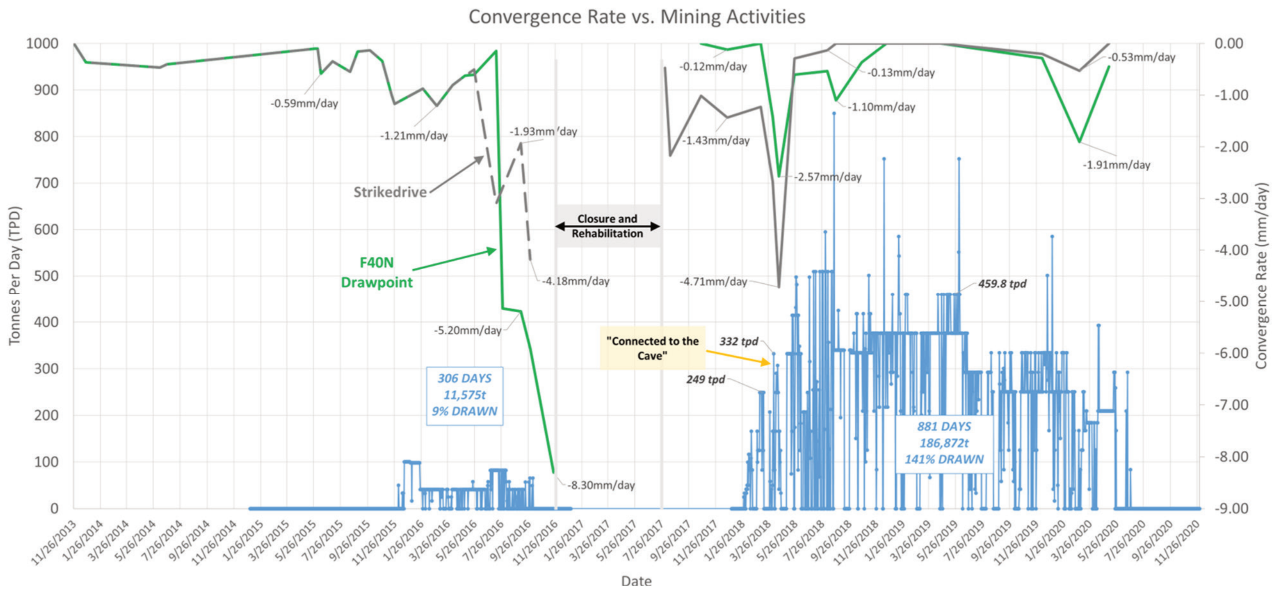


Figure 19 Life of F40N drawpoint – mined tonnes per day (tpd) versus extraction drive and F40N drawpoint convergence over time

The project management-based approach with redevelopment and ground support guidelines, along with implementing confinement based support led to F40N and the extraction drive being successfully rehabilitated. F40N continued to be mined and overperformed until closure, no additional rehabilitation was needed for the drawpoint other than floor repair due to some minor heaving. A snapshot summary is shown in Figure 20 of the re-excavation of the drawpoint to the converged original steelsets, the long and short support installed with lattice arches, and the final result. In addition, the last picture is an example of pre- and post-rehabilitation convergence scans, visually observing the performance of a confinement based support system experiencing convergence versus the localised wall and back convergence failures without confinement based support (Figure 20).

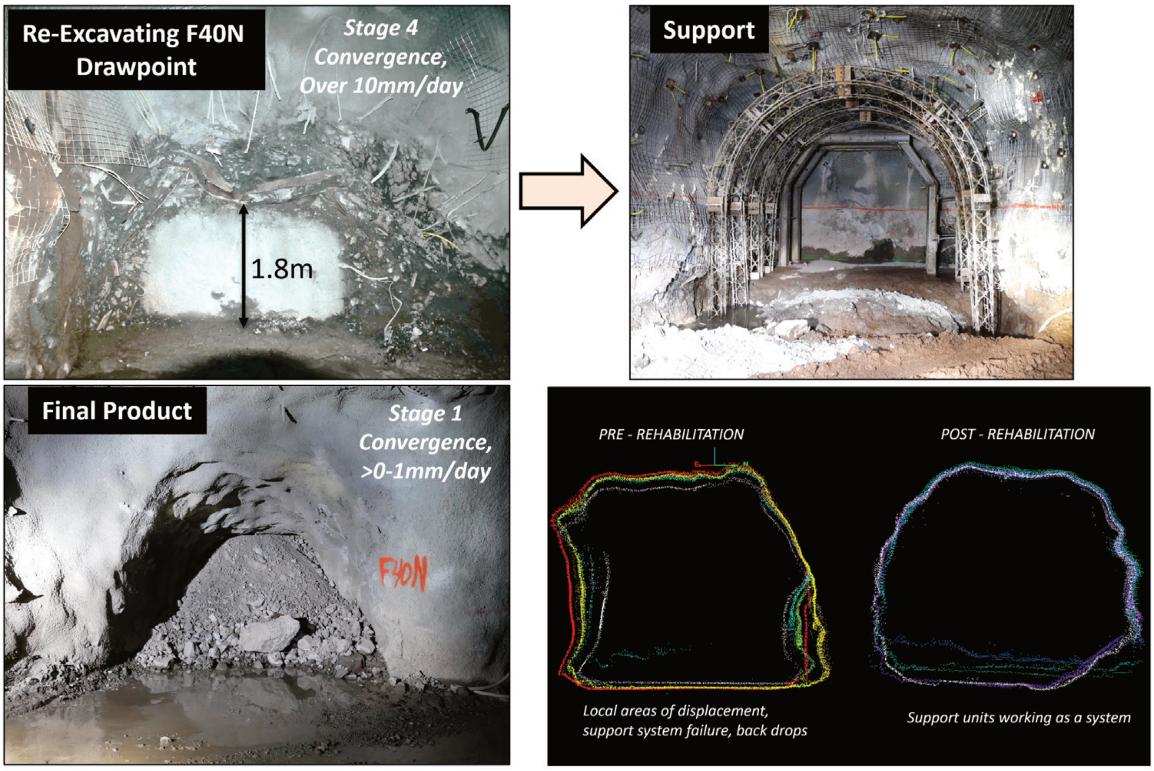
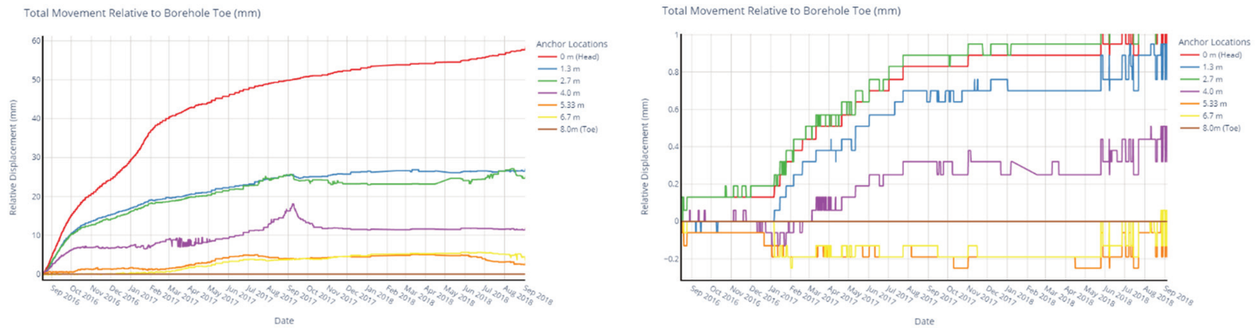


Figure 20 Overview of F40N drawpoint rehabilitation and effectiveness of confinement based support

6 Extraction level convergence: conceptual model

Observations, convergence scanning and extensometer data for converging drawpoints within the West and East Cave has allowed New Afton to develop a conceptual and practical approach to observing and managing convergence. Observations of late-stage convergence of a drawpoint or extraction drive shows an increasing depth of pillar (horizontal) deformation over time, while the back drops vertically, but stays relatively intact (Figure 22). An example of this data is seen in Figure 21 where a Multi-Point Borehole eXtensometer (MPBX) in the walls measures an increasing depth of displacement over time, while the MPBX in the back perceives almost no significant movement. This is seen observationally in Figure 22. This may seem contrary to the observations made by the convergence scanner when back convergence rates are being observed and measured. This behaviour indicates that the MPBX instrument moves with the vertical displacement of the back and is hypothesised that the horizontal pillar between the extraction level and the overlying cave is remaining relatively intact.



(a) (b)

Figure 21 (a) 8.0 m long MPBX located in the drawpoint walls (0–60 mm Y-scale); (b) 8.0 m MPBX located in the drawpoint back (0–1 mm Y-scale). Installed with MPBX head pushed in +1.0 m from collar

Figure 22 View looking down a late-stage converged extraction drive permanently closed post-production. Original 4.5 × 4.5 m drift converged to less than 2.0 × 2.0 m in several areas. Observations show yielded and toppling pillars with an observed flat looking back profile with intact ground support and very little to no shotcrete cracking, aligning with the MPBX data observed in Figure 21

This process of convergence deformation from initial onset to late-stage deformation, similar to the example shown in Figures 21 and 22, has been used to create a conceptual model. The conceptual model has been represented in three different ways; description based, as visual pictures and as a conceptual figure.

The conceptual model allows the engineers to proactively manage convergence through ground support and production strategies.

By combining the descriptions and visual images a conceptual figure is generated, showing the different stages of convergence rates in colours with simplified vectors (arrows) and symbols for cracking, shearing, toppling and bulge characteristics observed during the convergence process (Figure 24). In Figure 24 the onset of elevated deformation rates generally observed within a drawpoint for each convergence stage are coloured to match that stage.

Table 4 Conceptual convergence model represented as descriptions

Horizontal convergence rate (mm/day)	Description of observations	Rehabilitation strategy
Stage 1 >0 to 1.0	Cracking of pillar nose and shearing of shoulder, low wall bulge (heave), steelsets intact.	Spotbolting on tight pattern to keep low wall, pillar nose and shoulder intact. Include strapping or confinement. Draw control strategies specific to the area (maintaining or increasing draw, applies to Stages 1–4).
Stage 2 1.0 to 2.0	Continued above with, shotcrete spalling on the walls from horizontal convergence, both shoulders shearing, floor heave (depending on pillar performance), steelsets buckling in shoulders.	Manage ground support capacity as drift is converging by replacing any failed or heavily loaded short, long and confinement support regularly. Rebuild pillars with supported shotcrete or tied in forms as required.
Stage 3 2.0 to 4.0	Walls begin to topple inwards as the back may start to vertically converge at similar rates to horizontal convergence, shoulder shearing continues and pillar will punch into the back or floor, steelsets buckled.	Manage as above or able to fit equipment, local wall, back or floor excavation may need to occur with re-support in a timely manner. Establish short to long-term rehabilitation plan for the affected area.
Stage 4 4.0+ mm/day	Walls continue to topple inwards as back comes down more rapidly, if walls are intact the back will shear vertically down them. Convergence rate may increase rapidly, and equipment may not fit into the drift, steelset or section of steelset failed not allowing full production buckets.	Redevelopment and support of a section or entire tunnel in a timely manner or fill tunnel with concrete if unable to repair until later or to save the nearby tunnels from full convergence.

These descriptions from Table 4 can be observed visually through images taken at each convergence stage (Figure 23), note the flat looking back profile and yielding and progressively toppling inward pillars.

Observations seen in picture or 3D scan figures provided in other published papers have similar visual indications that align with this conceptual model; where in general the walls are experiencing high convergence or inward toppling whilst the back is vertically converging with a relatively intact profile (Ginting & Alpeki 2018; Moss & Kaiser 2022; Evans 2021; Brenchley et al. 2013; Pardo et al. 2012; Firmanulhaq et al. 2017).

This conceptual model concept shown may not apply to areas of significant faulting or lithology contacts as they may cause variation in the convergence profile, examples such as the shoulder shearing could occur mid-wall, or the back could bulge or fail due to the geology heterogeneity. Also, if the rock mass is stronger or ground support keeps the pillars well confined from yielding, less horizontal convergence may be observed resulting in the back to vertically converge and shear along and down the walls. In some cases, more floor heave may also be present.

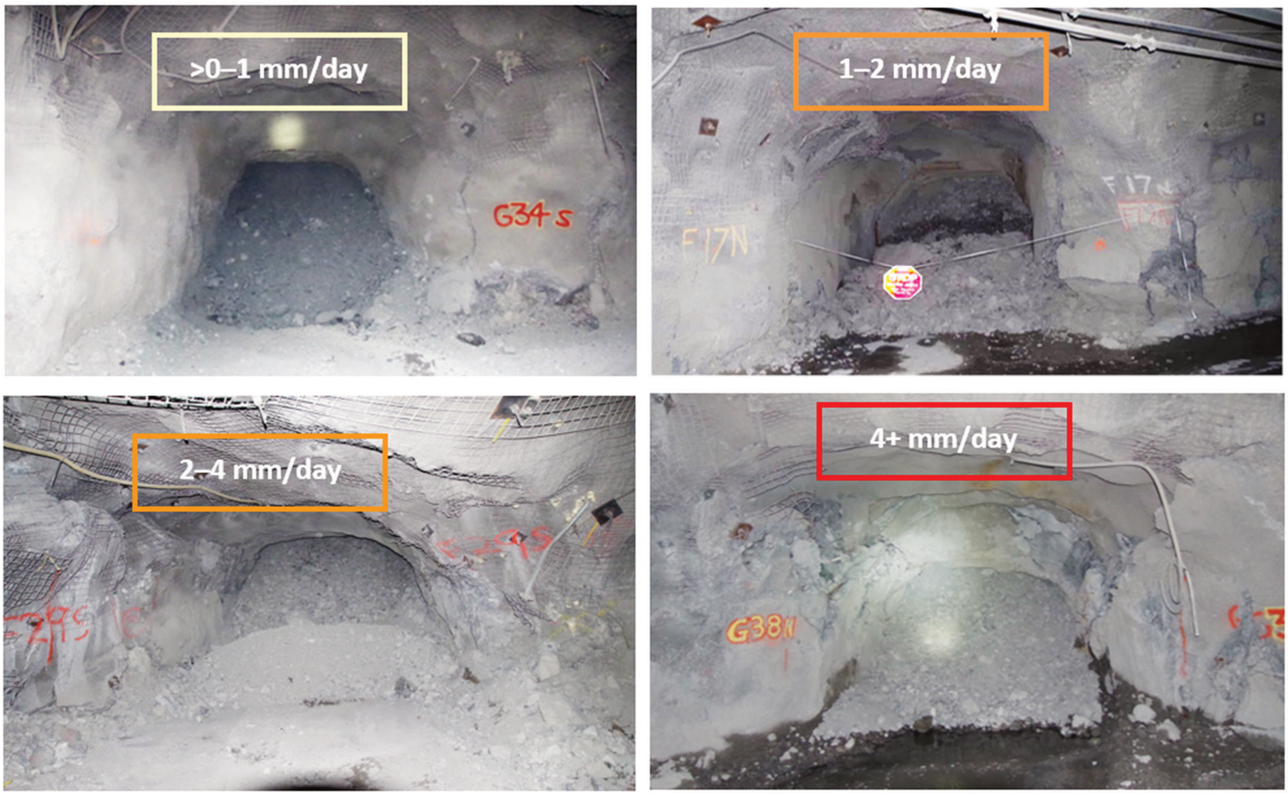


Figure 23 Conceptual convergence model represented as visual pictures, ordered from Stages 1 to 4

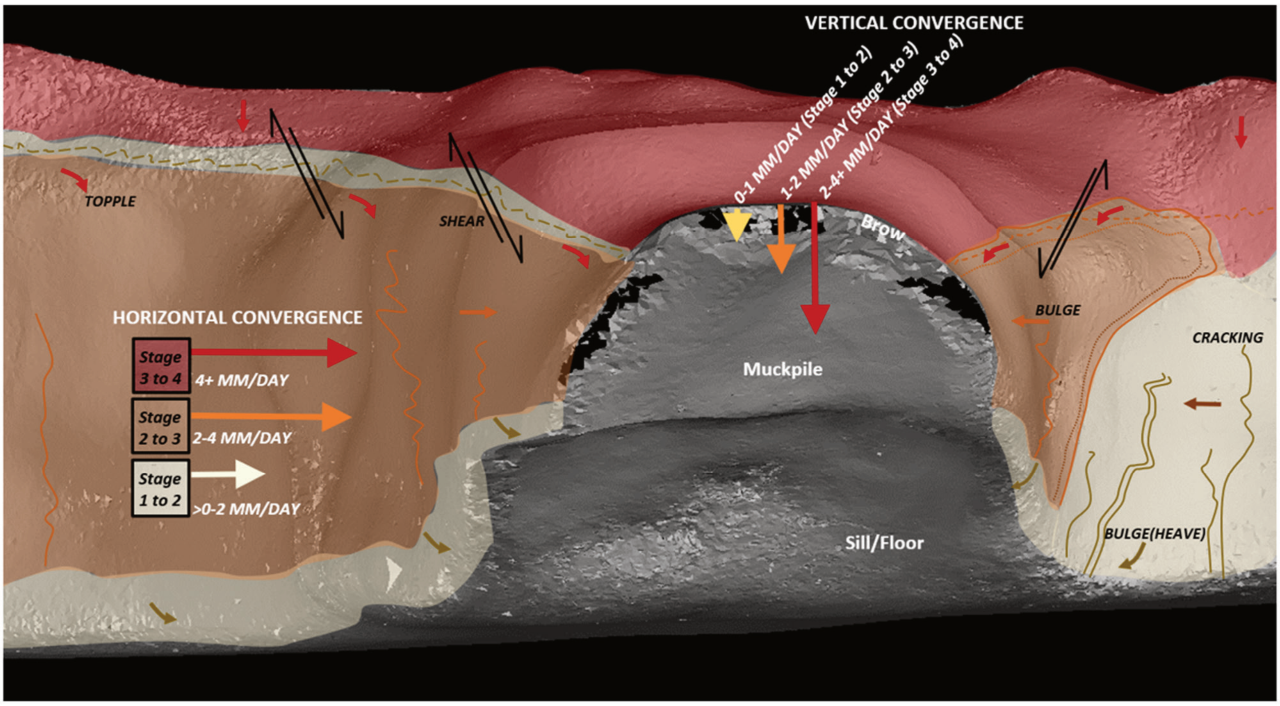


Figure 24 Conceptual convergence model represented as a conceptual figure using a 3D scan of a drawpoint as the template, the onset of elevated deformation rates generally observed within a drawpoint for each convergence stage are coloured to match that stage. Vertical convergence associated with the horizontal rates are shown through simplified vectors (arrows)

7 Discussion

Block caving in a poor rock mass subject to high cave induced stress changes, typically experiences large plastic deformations which manifest as drive convergence and in some cases complete drive closure. Such conditions require comprehensive extraction drive and drawpoint rehabilitation which can consequently effect production and operational costs. The onset of convergence can be identified and managed to support life-of-mine production; however, in areas where convergence rates continue to increase, convergence may expand into other areas of the extraction level due to drawpoints becoming inconsistently mucked during rehabilitation efforts.

Rehabilitation requires significant technical experience and a team of skilled engineers, planners and mining operators. The process can take significant time and cost, for an entire redevelopment of a tunnel, a project should be estimating 3–4m/week rate at roughly 2.5× to 3.0× the original development cost (F40N case study). In addition, the convergence locations, extent of work and resources need to be well understood so rehabilitation can be a continuous process until completed.

Managing the occurrence of convergence through rehabilitation and ground support can be successful using a project management-based approach with redevelopment and ground support guidelines that are created on ground-response observations and measurements, along with implementing confinement based support systems, when needed. However, ground support should not be the primary planning method to manage convergence for caving operations. It is believed that first optimising mine design, undercutting method, blasting quality, extraction level overbreak control, production mucking rates, and understanding the impacts from major faults and abutment stresses from the cave will reduce the occurrences of convergence.

8 Conclusion

A conceptual model and comprehensive ground control rehabilitation strategy has been developed and applied at the New Afton Mine with the aim of managing rock mass damage and maintaining drawpoint integrity until they have been mined to their end of production. New Afton has successfully mitigated over 1,700 areas of minor convergence and effectively reopened over 20 fully converged drawpoints in the East Cave through engineering, planning and skilled mine operators dedicated to rehabilitation.

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