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Observed subsidence progression at New Afton Mine in response to Lift 1 mining

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Abstract

New Gold's New Afton Mine is an operating gold-copper block cave mine located 10 km west of Kamloops, British Columbia, Canada. Mining of an initial lift (Lift 1), approximately 600 m below ground and partially beneath the historical Afton Pit, was completed in early 2022. The initial Lift 1 drawbell was blasted in September 2011 and cave breakthrough to the surface was monitored in February 2013. A state-of-the-art subsidence monitoring program has progressively been implemented at New Afton to monitor progression of surface and near-surface deformations in response to mining, including towards critical surface infrastructure.

This paper presents a case study of the observed subsidence progression in response to block cave mining, from initial breakthrough to the end of the Lift 1 production, using examples from the various instrumentation and monitoring techniques used at New Afton. The surface manifestation of deformation was found to be influenced predominantly by mine production rates and the location(s) of underground draw. Additional controls on the expansion of the subsidence zone and the spatial distribution of deformation rates included influence of topography, presence of major geological structures, preferential deformation within comparably deformable Nicola Group geological units, and interaction with the historical Afton Pit. A summary of the use of available instrumentation and monitoring methods and the phased development of New Afton subsidence monitoring system are also presented.

Keywords: *block cave, subsidence, monitoring, instrumentation, remote sensing*

1 Introduction

New Gold's New Afton Mine is an operating gold-copper block cave mine located 10 km west of Kamloops, British Columbia, Canada. Mining of an initial lift (Lift 1), approximately 600 m below ground and partially beneath the historical Afton Pit, was completed in early 2022. The initial Lift 1 drawbell was blasted in September 2011 and cave breakthrough to the surface (initial surface deformation in response to mining) was monitored in February 2013. Subsidence deformations resulting from Lift 1 mining have been rigorously monitored and evaluated due to the presence of surface infrastructure, including tailings storage facilities, in proximity to the mining area. Surface and subsurface deformations are monitored using a comprehensive network of in situ instrumentation and with remote sensing techniques. Extensive monitoring data collected during Lift 1 production have allowed for comprehensive characterisation of the spatial and temporal progression of subsidence in response to mining and facilitate cross-validation between multiple instrumentation and monitoring techniques.

This paper presents a case study of the observed progression of subsidence deformations in response to Lift 1 mining from breakthrough of the cave to surface through the end of the Lift 1 mining phase. Observed surface and/or subsurface (near-surface) deformations were found to be:

- Spatially and temporally linked to production rates and location(s) of underground draw.
- Laterally constrained by major geological structures and lithological contacts, which acted as significant bounding structures to subsidence deformation.

- Influenced by topography.
- Affected by rock mass quality and deformability within the Nicola Group Volcanics (picrite, BXF).
- Influenced by pit wall geometry, pre-existing slope failure mechanisms and structural geology within the historical Afton Pit.

Specific examples of observed subsidence behaviour overlying the Lift 1 mine and in proximity to surface infrastructure including the Historical Afton Tailings Storage Facility (TSF), New Afton TSF, and ventilation raise infrastructure (vent raises) are presented. The interaction of the block cave with the historical Afton Pit is also examined.

2 Geological setting

The New Afton deposit is a silica-saturated, copper-gold alkalic porphyry-style deposit. Mineralisation resulted from late-stage hydrothermal activity driven by remnant heat from the porphyry intrusion. The principal host rock for the New Afton deposit comprises crystalline and polymictic fragmental volcanics belonging to the Triassic Nicola Formation and lesser monolithic intrusive breccias. These rocks have been altered and mineralised by structurally controlled elongated stock and related dyke swarm. Nicola Group volcanic rocks comprise volcanic fragmental breccia and picrite. The fragmental breccia, informally referred to as 'BXF', includes primarily fragmental volcanic breccia with intervals of crystalline volcanic rocks. The picrite unit is located to the south of the extraction footprint, is highly serpentinised and sheared along fault contacts, and generally has a poor rock mass rating (Clayton et al. 2018). Ashcroft Formation sedimentary rocks comprise sandstone, siltstone, and conglomerate and are situated east of the southwestern Nicola Group BXF unit.

Structure is recognised as a principal control to the genesis of the Afton deposit and has a strong influence on the geometric behaviour of caving and subsidence. The deposit and subsidence area are transected by numerous mapped faults with a range of orientations.

The bedrock geology and structures of the Lift 1 footprint and within the subsidence zone are shown in Figure 1.

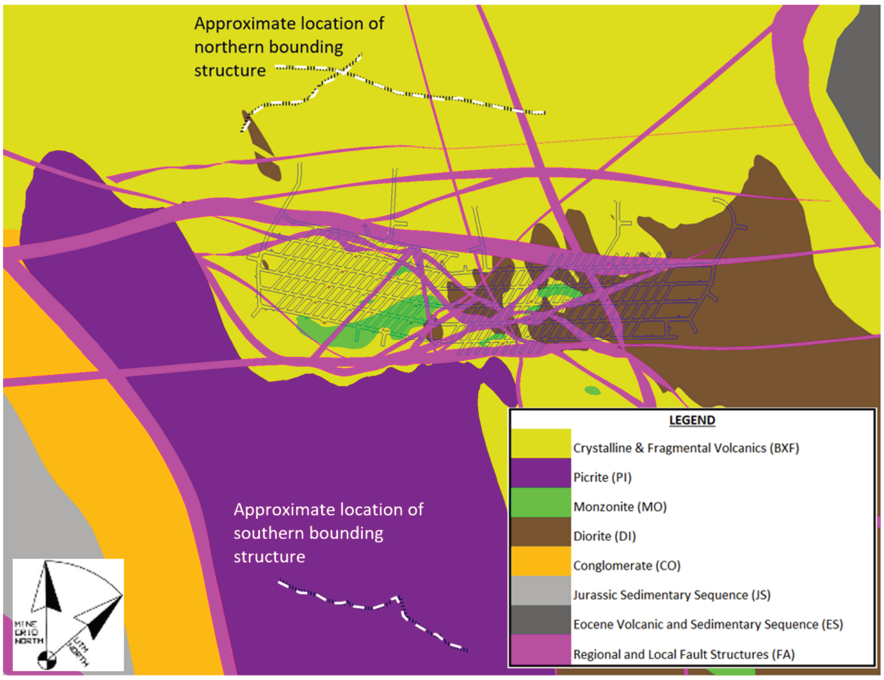

Figure 1 Lift 1 Footprint (West and East Caves) with lithology and major structures shown at the extraction level elevation. Northern and southern subsidence boundaries are shown for context, projected from surface (about 600 m above Lift 1)

3 Mining overview

3.1 Overview

New Gold's New Afton block cave mine began underground production in 2012. Development of the underground mine began in 2007, the first drawbell blast occurred in September 2011, and Lift 1 reached commercial production in July 2012. Ore is conveyed via load-haul-dump equipment to an underground crusher and is then conveyed to surface for milling. Tailings produced are stored within the presently active New Afton and Pothook TSFs.

The site was previously active as a surface operation within the historical Afton open pit (between 1977 and 1997) under another operating company. Design slope angles for the open pit were between 40° to 45° and the ultimate depth was approximately 210 m (Reed 1983). Tailings from this operation were deposited within the Historical Afton TSF, which is currently in care and maintenance. Waste rock dumps were developed, mainly to the south and southeast of the Afton Pit, with a maximum height of approximately 80 m above natural ground.

Block cave mining has resulted in surface subsidence in proximity to historical and current mine infrastructure, including the TSFs. The locations of the Lift 1 mine (West and East Caves), Afton Pit and Historical Afton TSF are illustrated on Figure 2 (Note that cardinal orientations will be presented relative to mine grid north (MGN) throughout this paper).

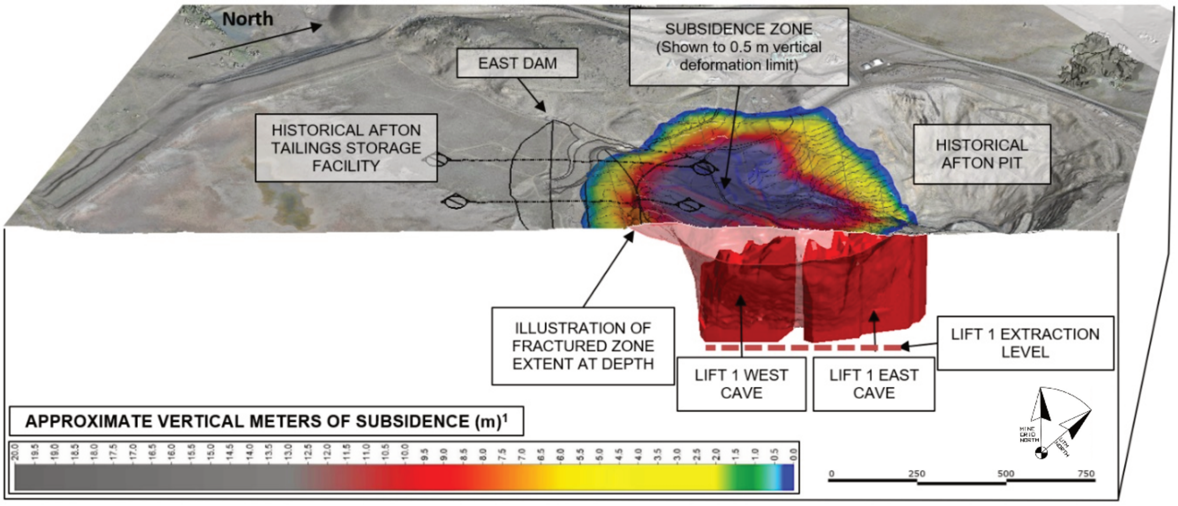

Figure 2 Lift 1 (West and East Cave) location relative to the Afton Pit and Historical Afton TSF with illustration of subsidence magnitudes and extent at the end of the mining phase

3.2 Lift 1 mine layout and production history

New Afton's initial Lift 1 block cave mining phase comprised production from the adjacent West and East Caves, located on the same level and separated by an approximately 50 m thick zone of waste material (Scott Wilson Roscoe Postle Associates Inc. 2009). The Lift 1 extraction level is located approximately 600 m below ground (5070 m level) and partially beneath the historical Afton Pit, which has a depth of approximately 230 m. The mining footprint is approximately 800 m long by 120 m wide. Initial production began within West Cave in early 2012 and breakthrough (initiation of surface deformation) from this panel was observed using a prism monitoring network in February 2013. East Cave production was initiated in mid 2013 and broke into the Afton Pit in approximately mid 2016. Mining within West and East Caves was completed in April 2021 and February 2022, respectively. Recovery mining within a two-level front cave was initiated beneath East Cave in early 2020; however, tonnages are minimal as compared to West and East Caves. The Lift 1 extraction level, West Cave and East Cave locations are illustrated in Figure 2.

Lift 1 was mined at an average production rate of approximately 13,000 tonnes per day (TPD). Mine draw began exclusively within West Cave, transitioning to production from both panels, and ending within East Cave alone. The transition between predominantly West Cave and predominantly East Cave draw occurred in May 2017. Cumulative and incremental tonnage data for Lift 1 (both panels), West Cave, and East Cave are shown on Figure 3. A comparison of cumulative tonnage with the monitored cumulative subsided volume is also provided.

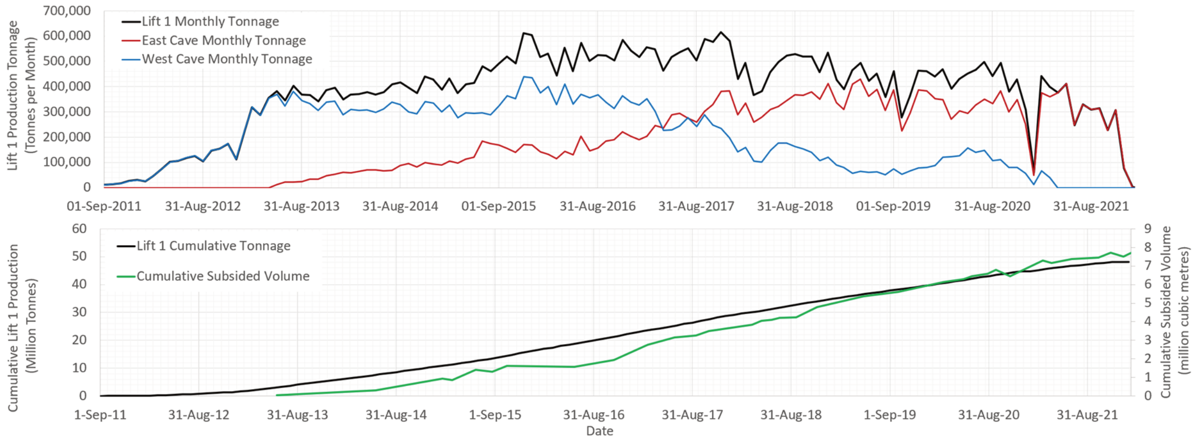

Figure 3 Lift 1 production rates and comparison of cumulative tonnage with monitored subsidence volumes (recovery level production omitted for clarity)

4 Subsidence monitoring network

Subsidence deformations resulting from Lift 1 mining have been rigorously monitored and evaluated due to the presence of surface infrastructure, including multiple TSFs, in proximity to the mining area. Surface and subsurface deformations are rigorously monitored to inform the following primary monitoring objectives:

- Tracking the progression of ground deformations towards critical site infrastructure.
- Monitoring the influence of surface deformations on site infrastructure that is already present within the subsidence zone.
- Informing calibration of predictive numerical subsidence models used to forecast subsidence impacts to surface infrastructure and design mitigation, as required.

To achieve these objectives, monitoring data and visual observations are used to interpret the spatial extents and progression of New Afton's conceptual cave and subsidence zone components illustrated for reference on Figure 4.

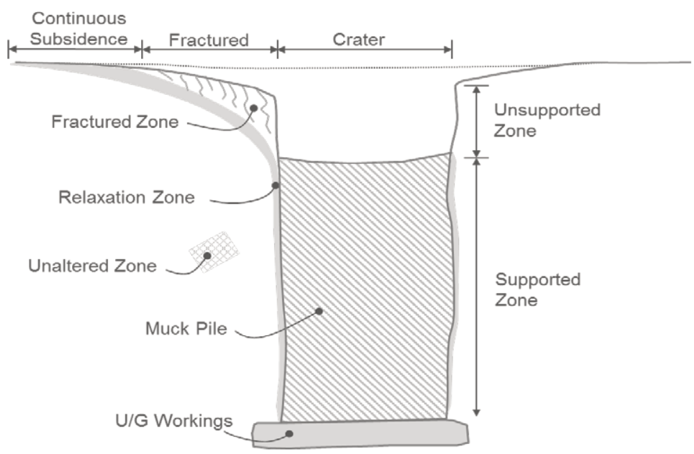

Figure 4 Terminology to describe the conceptual components of the cave and subsidence zone

The subsidence monitoring instrumentation network at New Afton is comprehensive and includes a variety of surface and subsurface instruments supplemented by remote sensing techniques. A subset of deformation monitoring techniques (i.e. TDRs, inclinometers, multi-point borehole extensometers (MPBX), prisms and inSAR) feature lower detection limits and are used to monitor the progression of relatively small deformations typical within the continuous subsidence zone (Figure 4). Additional techniques (photogrammetry, prisms, survey monuments and Geo4Sight) monitor the larger deformation magnitudes within the fractured zone (Figure 4). Subsurface instruments used within this latter context, namely Geo4Sight, are specialised not to require that physical connectivity be maintained along the drillhole axis. These installations can therefore tolerate higher displacement magnitudes than conventional subsurface instrumentation such as inclinometers and TDRs. Use of multiple monitoring techniques within each zone allows for cross-verification findings between datasets. This increases confidence in data interpretation and findings used to support onsite decision-making. The instrumentation currently utilised as part of the subsidence monitoring network and a description of the utility of each method are summarised in Table 1**.** Locations of the current surface and borehole instrumentation are shown on Figure 5.

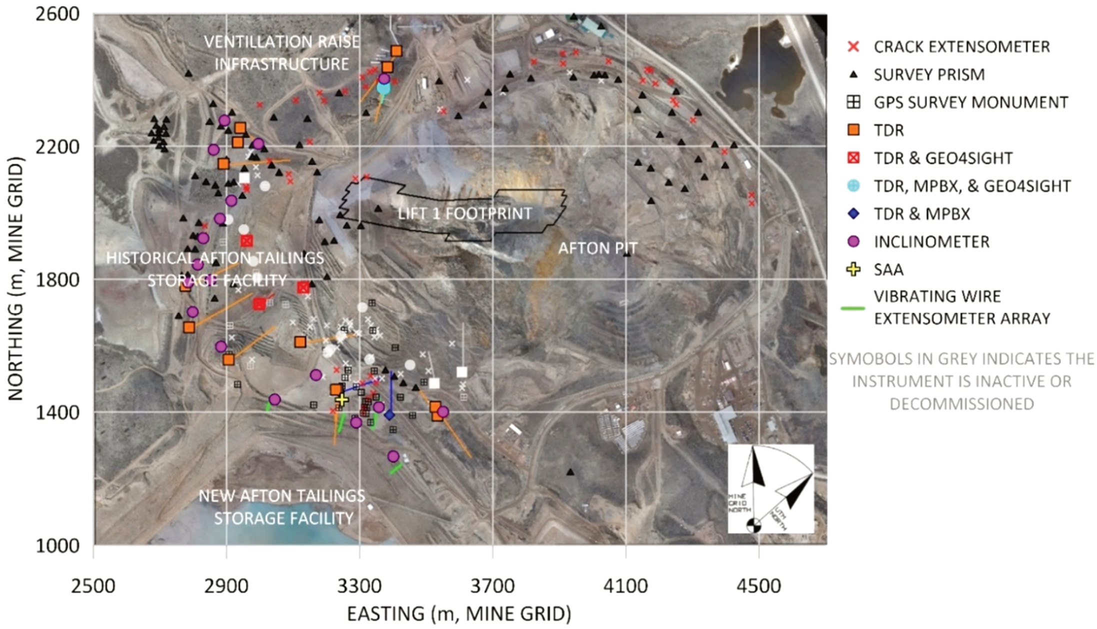

Figure 5 Overview of subsidence monitoring instrumentation network

The subsidence monitoring network has been progressively supplemented to respond to changing project objectives and to utilise state-of-the-art instrumentation, as new applicable methods become available. Recent additions to the subsidence monitoring network are at the forefront of geotechnical instrumentation technology and include:

- Elexon Geo4Sight Markers: Initial Geo4Sight installations (wireless multi-node angular deformation monitoring instruments) were completed to monitor subsurface deformations within four drillholes in proximity to the vent raises during 2019 and were nested with TDRs and MPBX (Kamp et al. 2020). Three additional Geo4Sight installations were completed in late 2020 and early 2021 and included a subset of markers capable of pore pressure measurement. Two of these installations were installed vertically to 450 m below ground surface and one angled towards the mining footprint to a depth of 200 m, as shown in Figure 5.
- Ground-based radar: A ground-based radar unit was deployed in September 2021 to monitor deformations of the Afton Pit slopes in response to ongoing mining activity.
- Satellite inSAR: A historical inSAR analysis has recently been completed for comparison with other Lift 1 surface monitoring data. Operational inSAR data is ongoing and will be useful in subsequent mining phases as a supplementary method of monitoring site-wide surface deformations.

Table 1 Summary subsidence monitoring instrumentation techniques used at New Afton

Instrumentation or monitoring technique		Description of use
Surface instrumentation	Surface crack mapping and differential global positioning system (DGPS) pin extensometers	Regular monitoring for development of new surficial cracking and change in displacement (aperture and vertical offset) of known surface tension cracks.
	Robotic theodolite (RTS) and prisms	Automated survey-monitoring of surface displacement at prism locations located throughout the subsidence zone and surface facilities.
	DGPS survey monuments	Manual survey-monitoring of surface displacement at monument locations located throughout the subsidence zone and surface facilities.
	Vibrating wire extensometers	Automated monitoring of axial deformation within soil beneath key surface infrastructure.
Remote sensing	UAV (drone) photogrammetry	Regular monitoring of surface displacement resulting from subsidence progression, with site-wide coverage.
	Terrestrial laser scanning (LiDAR)	Regular monitoring of slope displacement progression within the Historical Afton Pit that occur in response to subsidence.
	Satellite Interferometric Synthetic Aperture Radar (InSAR)	Monitoring of surface displacement resulting from subsidence progression, with site-wide coverage.
	Ground-based radar (GbSAR)	Near real-time monitoring of Historical Afton Pit slope displacements.
Borehole instrumentation	Inclinometers	Manual monitoring of the magnitude, orientation, and spatial distribution of subsurface ground displacements.
	ShapeAccelArray (SAA)	Automated monitoring of subsurface ground displacement magnitudes.
	Time domain reflectometers (TDRs)	Automated monitoring of ground displacement progression along coaxial cables embedded in drillholes. Clipping is interpreted to occur in response to relatively small deformations and the technique does not quantify magnitudes.
	Multi-point borehole extensometers (MPBX)	Automated monitoring of subsurface axial displacement magnitudes and rates along borehole axis.
	Magnetic settlement datums (MSD)	Manual monitoring of subsurface settlement/axial deformation. Typically used in conjunction with inclinometers to assess bottom fixity.
	Elexon Geo4Sight Markers	Wireless angular deformation monitoring at 2 m spacing within boreholes. Capable of monitoring large deformation magnitudes (more than conventional instrumentation) and porewater pressures.
	Vibrating wire piezometers	Automated monitoring of pore pressure changes or instrument disconnect that may indicate development of subsidence-derived fracturing or deformation.

Subsidence monitoring exclusion zones have been established between the TSFs and the mining footprint to facilitate monitoring through minimisation of traffic and equipment derived surface disturbance. These protected areas allow for identification and monitoring of hairline surface cracks and provide undisturbed surface conditions suitable for monitoring via unmanned arial vehicle (UAV) photogrammetry and satellite inSAR.

5 Observed subsidence response to mining

5.1 Overview of observed subsidence

Subsidence was first monitored onsite following breakthrough (occurrence of initial surface deformations) of West Cave to surface in February 2013. Breakthrough was detected and subsequent deformation magnitudes were monitored using a localised network of RTS prisms. This was supplemented with photogrammetric monitoring as deformation magnitudes increased to comprehensively characterise the extent of the subsidence geometry (Figure 6). InSAR data are also retrospectively available with coverage of West Cave breakthrough (Figure 7). The location of breakthrough was offset to the southwest of West Cave's footprint, rather than directly overlying it. This offset geometry is interpreted to result from the following two main influences that are inferred to have resulted in a southwestward 'lean' as the West Cave propagated to surface:

- The picrite rock mass – situated to the south and west of the mine footprint along the hanging wall contact – overhangs the orebody near surface and is typically of poorer quality than the orebody. The weaker nature of the picrite is interpreted to have resulted in preferential cave propagation within this unit near surface, which influenced the breakthrough location to occur farther to the southwest.
- The historical Afton Pit waste rock stockpile is located within the breakthrough area primarily to the south of the mine footprint and is up to 80 m thick. The extent of surface deformations is interpreted to have been further exaggerated to the southwest of the cave footprint due to failure (movement) of these materials towards the location of cave breakthrough.

The temporal progression of subsidence following breakthrough is presented on Figures 6 and 7 using results of photogrammetric and inSAR displacement monitoring, respectively. The presented timelines are truncated for clarity prior to the conclusion of Lift 1 mining due to data availability (inSAR; 2013 through 2017) and as borrow activities within the subsidence zone began to impact topographical change detection in some areas (photogrammetry; 2011 through 2019). The observed sequence of subsidence progression from West Cave breakthrough through Lift 1 closure is presented below.

The subsidence zone expanded radially outward and deepened following breakthrough in response to continued West Cave mining from 2013 through 2015. The largest deformation magnitudes were observed within and overlying the picrite rock mass and the adjacent historical Afton waste rock stockpile, resulting in elongation of the subsidence zone along the approximate axis of the picrite unit and slightly offset to the south of the West Cave footprint. Further subsidence progression resulted in the subsidence zone encountering significant structural boundaries to the north and south, which limited within them the extent of large-scale surface deformations. Key bounding structures are described below (discussed further in Section 5.2), and these continued to limit subsidence extent through the end of Lift 1 mining:

- Northern boundary: The northern extent of the subsidence zone encountered a series of east–west trending faults located between West Cave and the vent raises beginning in 2016 (Figure 5). These structures have limited the northward expansion of the subsidence zone (Figure 6) and became increasingly apparent as vertically offset scarps later developed along the structures.
- Southern boundary: The most significant subsidence zone expansion during 2016 and 2017 (corresponding to a period of peak West Cave tonnages) occurred within the picrite unit and the adjacent historical Afton waste rock stockpile. Deformation during this period progressed the

subsidence zone to the south and southeast, into contact with a significant structural boundary downstream of the New Afton and Historical Afton TSFs (Figure 6). Similar to the northern boundary, a geological structure is interpreted to have limited further expansion of large-scale subsidence deformation.

East Cave mining began to interact with the existing West Cave subsidence zone in mid 2016 and reached full production in mid 2017. A breakthrough crater was observed within the bottom of the Afton Pit in September 2017. Influence from this panel resulted in eastward expansion of mining-derived surface deformations along the central axis of the mine footprint (Figures 6 and 7). Subsidence began significantly interacting with the south and west Afton Pit slopes, which exhibited complex deformation responses due to pre-existing pit wall instabilities and complex structural geology (discussed further in Section 5.3).

West Cave tonnage began to decrease beginning in 2017 and East Cave mining became the predominant production source in late 2017. This was followed by the conclusion of West Cave mining, which occurred in April 2021, after which East Cave was mined exclusively until Lift 1 closure in February 2022. Deformation rates observed within the western extent of the subsidence zone began to slow in response to declining West Cave tonnages: a trend that has continued to date. The main subsidence zone continued to deepen but did not significantly expand towards the TSFs or the vent raises, instead remaining bounded by the northern and southern structural boundaries (Figure 6). Localised displacements developed over the mine footprint as East Cave draw focused within a smaller area (fewer active drawbells), remaining concentrated within the historical Afton Pit (south and west pit slopes) and to the south of the mine footprint within the existing subsidence zone. Monitoring within these areas observed an almost immediate slowing of deformation rates following the conclusion of Lift 1 production.

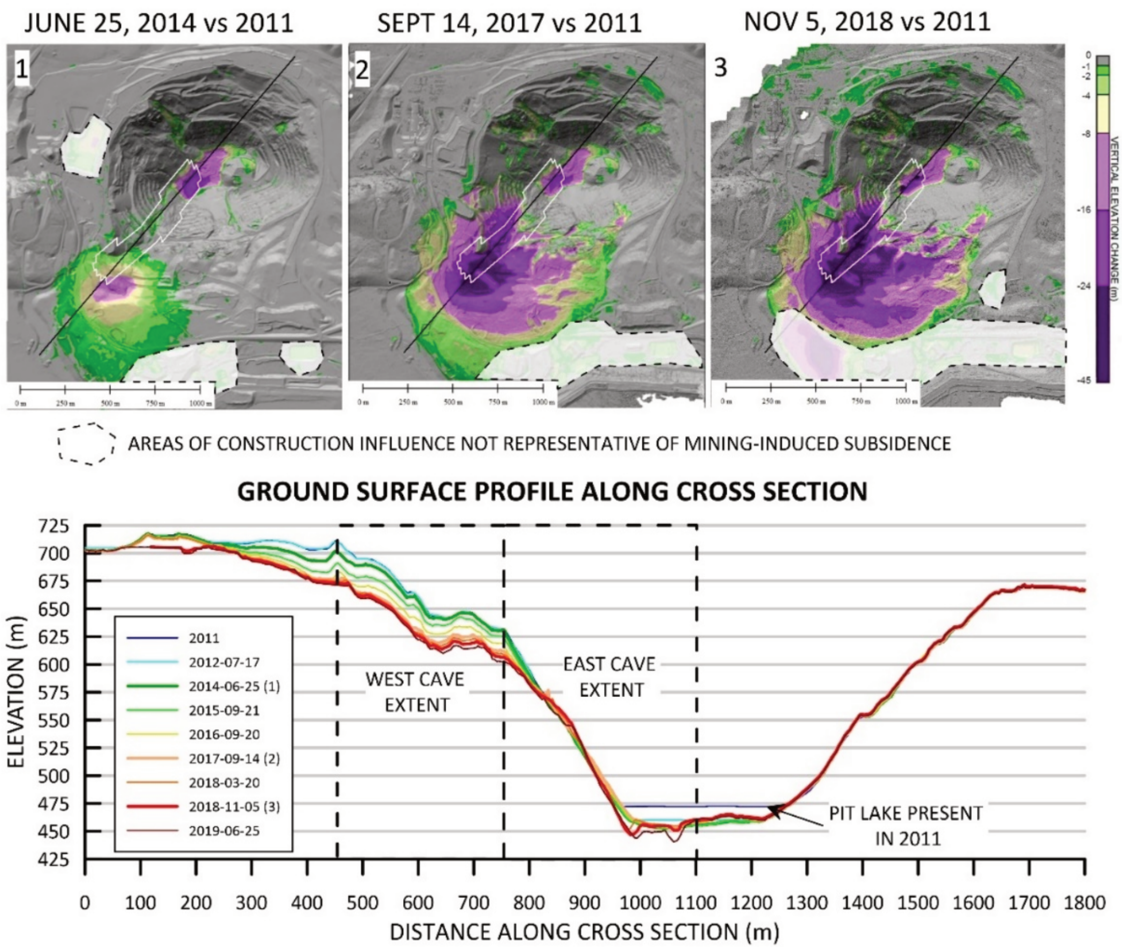

Figure 6 Extent and cumulative vertical surface displacement magnitudes illustrating (1) localised deformation following breakthrough of West Cave, (2) deepening of subsidence with West and East Caves active and (3) breakthrough of East Cave (monitored using UAV photogrammetry)

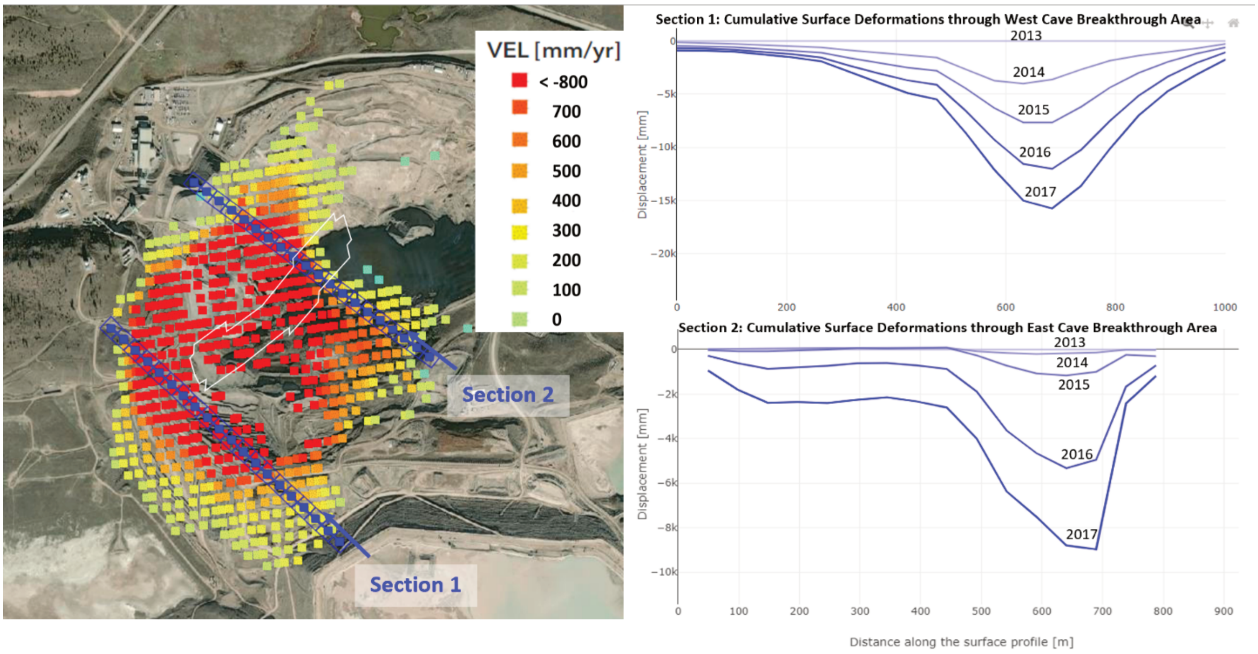

Figure 7 West Cave breakthrough (early 2013) followed by East Cave breakthrough (mid 2016) and transition of highest deformation rates over from West to East Caves (mid 2013 to mid 2017)

5.2 Factors influencing subsidence extent

The extent of subsidence and/or the spatial distribution of deformation rates were found to be influenced predominately by the rate and spatial distribution of underground production draw, the geological environment (i.e. rock mass characteristics, structural geology) and surface topography. The following sections present observations from New Afton Lift 1 mining that exemplify the effects of these influencing factors.

5.2.1 Production tonnage and centroid of production (draw)

Observed subsidence deformation rates and the spatial distribution thereof are primarily interpreted to be influenced by the draw centroid location (region with the highest average production rate) and the rate of underground production. Monitored surface and near-surface deformation rates have been shown to be highly reactive to changes in these parameters. Similarly, cumulative subsidence volumes – the volume of the subsidence zone as measured using sequential photogrammetric surface subtractions relative to the pre-mining topography – correspond well with cumulative Lift 1 tonnage and exhibit the same temporal trends (Figure 3). The sequence of Lift 1 production (initially focused within West Cave, transitioning to East Cave with time) resulted in an eastward progression of the highest deformation rates over time followed by the onset of slowing surface and subsurface deformation trends from west to east as the centroid of production progressed from West to East Cave and upon completion of Lift 1 mining.

Observed subsidence deformation rates and temporal increase in the cumulative subsided volume (Figure 3) within the western extent of the subsidence zone exemplify the association between with West Cave tonnage and deformation rates. Historical Afton TSF East Dam prism displacements provide a clear example of the relationship between draw location/rates and surface deformations. Cumulative vertical prism deformations along the East Dam crest are shown on Figure 8. The highest deformation rates were observed during 2015 through 2017, corresponding to a period of peak of West Cave tonnages. West Cave production subsequently ramped down, resulting in slowing deformation rates from 2018 through the closure of West Cave in April 2021. Similar trends have been observed elsewhere within the subsidence zone in response to both West Cave and East Cave production rates.

These relationships between surface deformation and production include:

- Discernible slowing of deformation rates within the Afton Pit, in proximity to the vent raises and downstream of the TSFs in response to temporary underground shut-downs and immediately following closure of East Cave (end of Lift 1 mining except relatively low tonnage from the recovery level) in February 2022.
- Correlation between West Cave tonnages and deformations observed along a transect of the subsidence zone near the vent raise infrastructure (Figure 9), where (1) higher tonnages correlate with larger inSAR monitored line-of-site deformation rates, (2) stable deformation rates were observed during periods of relatively high constant tonnage, and (3) displacements begin to slow along with West Cave tonnages in early 2017. Similar conclusions are exhibited in the photogrammetric displacement and prism datasets.

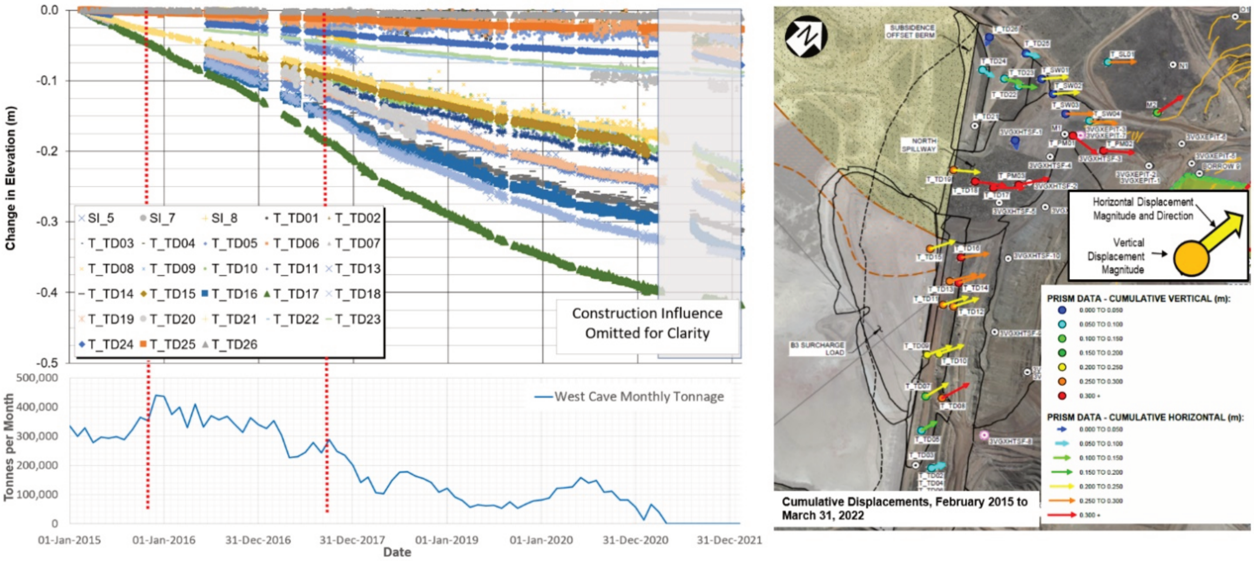

Figure 8 Comparison of HATSF East Dam prism displacements with West Cave production rates

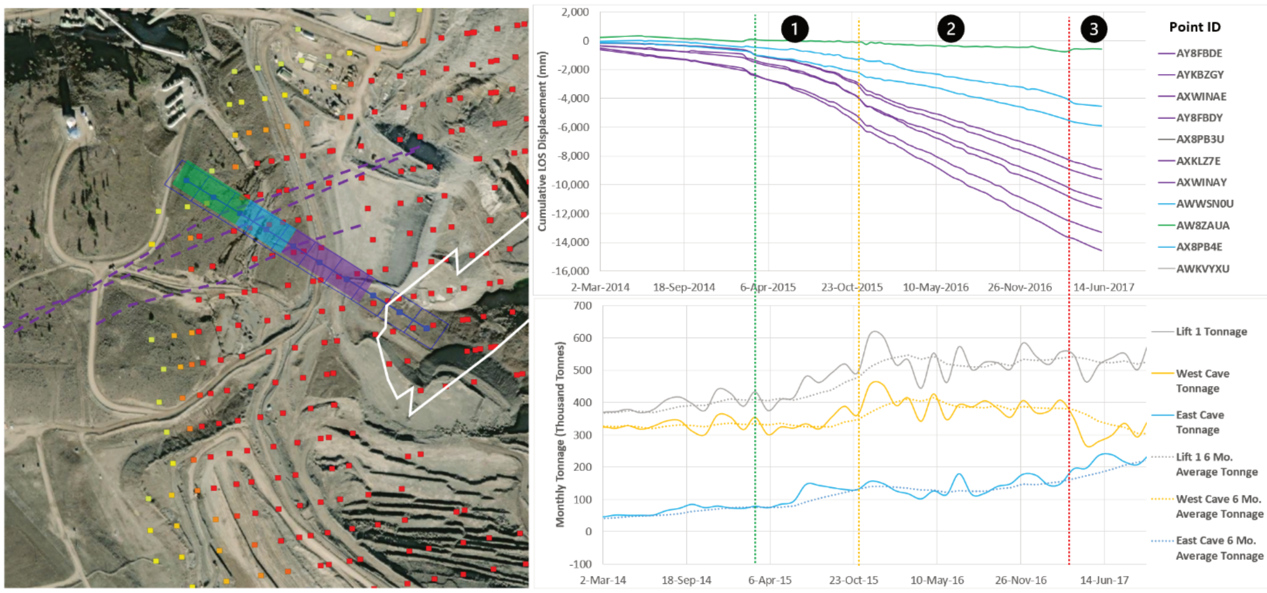

Figure 9 Comparison of cumulative line-of-site inSAR surface deformations observed near the vent raises from approximately mid 2013 through mid 2017 with production tonnage over the same period

Similar correlations between tonnage and subsurface deformations have also been observed across the site within the continuous and fractured subsidence zones. Examples of these responses include:

- Inclinometers monitoring slowing subsurface deformation rates in proximity to the Historical Afton TSF and New Afton TSF as West Cave tonnage decreased from approximately 2017 through 2021.
- Elexon Geo4Sight Markers observing higher angular deformation rates during local periods of higher West Cave draw and lower rates corresponding with lower tonnages.
- TDRs monitoring lower clipping (cable shear or extension due to deformation) frequency and/or lower rates of uphole clip progression (angled drillholes) during 2020 and 2021, as West Cave operations approached closure.
- MPBX axial deformation (extension towards the subsidence zone) rates decreased immediately following closure of East Cave.

Subsurface deformation trends monitored by Geo4Sight Markers installed within angled drillholes oriented from the vent raises towards the centre of subsidence exemplify the relationship between West Cave tonnage and subsurface deformation rates. Geo4Sight Markers are wireless multi-node angular deformation instruments capable of monitoring the progression of angular deformations uphole towards the vent raises. The instrumentation was installed in 2019 and has collected daily tilt readings (using so-called dip and heading parameters) thereafter. Observed angular deformation rates from an example marker (Marker 5), installed immediately within a major subsidence bounding structure (see Section 5.2.2) are shown alongside daily West Cave tonnage on Figure 10. West Cave tonnages were generally declining when the instrumentation was installed (since early 2017); however, a minor increase in production occurred between August 2019 and June 2020, followed by decreasing tonnage until closure in April 2021. The Geo4Sight angular deformation rates exhibited a corresponding increase to a peak angular deformation rate observed in June 2019. Rates then decreased along with tonnage, with little to no further deformation observed since completion of West Cave mining. Select markers installed outside of the bounding geological structure observed a similar temporal trend; however, with comparably very minor magnitudes.

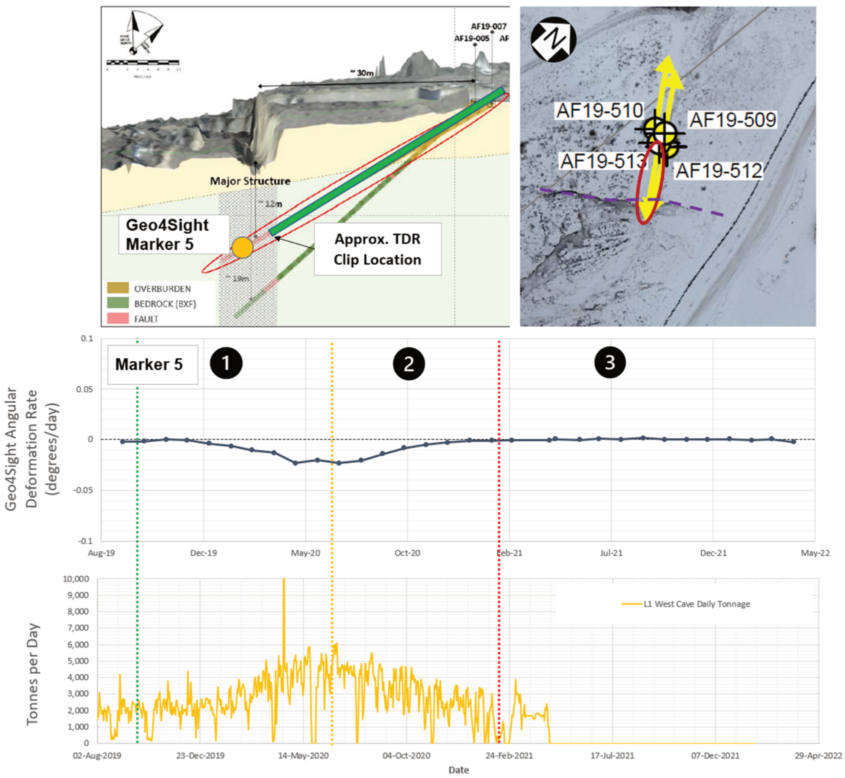

Figure 10 Comparison West Cave tonnage with Geo4Sight angular deformation rate observed from August 2019 through April 2021 (West Cave closure)

5.2.2 Geological structures

The extent of subsidence and spatial distribution of displacements have been observed to be constrained by the existence of bounding structural features (faults and lithological contacts), which have limited the expansion of subsidence within several areas. In these cases, significantly higher deformation magnitudes have been observed within (i.e. on the mining side) these structures. Comparably minor deformations generally observed beyond these boundaries; however, similar temporal trends (e.g. higher deformation rates corresponding with higher production tonnages) are observed on both sides. These observations imply that localised deformations are experienced along the structures that limit development of large deformations beyond the structure but that the influence of mining does extend further afield.

Major subsidence boundaries have developed along the northern boundary faults between the vent raises and the Lift 1 footprint that have limited the expansion of subsidence progression to the north. Surface expressions of these bounding structures are shown on Figure 11 and contrasting deformation magnitudes observed using photogrammetric monitoring, prism measurements and subsurface instrumentation across the boundaries are shown on Figure 12. Key findings include:

- Cumulative vertical surface displacements monitored using photogrammetry are shown in plan and along a section into the subsidence zone on Figure 12 (a) and (b), respectively. Up to 7 m of cumulative vertical subsidence has been monitored within northern boundary structure from 2011 through early 2022. No detectable deformations have been observed on the vent raise side of the structure, indicating that these remain below the experiential 0.7 m detection limit of the photogrammetric monitoring technique. The bounding influence of the geological structure is clearly illustrated along the cross-section, where significant subsidence-derived surface elevation changes are observed but are limited in extent within the structure. Similar step changes in deformation magnitudes across structures are discernible along the nearby inSAR section presented on Figure 9.
- Monitored prism displacements also exhibit contrasting deformation magnitudes that illustrate the structural bounding. Prisms 1 and 2 were installed in mid 2012 outside (north of) and within (south of) the major structures, respectively. Cumulative vertical displacements of both prisms are shown on Figure 12 (c) and through comparison have captured the contrasting deformations across the structures. Relevant observations include:
  - Prism 1 measured less than 1 m of cumulative vertical displacement outside of the structural boundary, while Prism 2 measured approximately 6 m within. Displacements north of these major structures are present but comparably very small.
  - Initial displacements were observed at both prisms following West Cave breakthrough (February 2013). Prism 2 measured significant acceleration to higher displacement rates beginning in 2015. This acceleration is interpreted to be associated with West Cave draw, which was at maximum production (approximately 12,000 tpd) at that time. This finding corresponds to significant visual observations of displacement along the major structures during early 2016. Prism 1 also measured slightly elevated displacements over the same period but at comparably minor rates. Displacement rates monitored by both prisms 1 and 2 and visual observations of surficial deformation along the structures slowed beginning in 2018, in concert with decreasing West Cave tonnage.
- Multiple subsurface instruments installed near to the vent raise within an angled drillhole oriented towards the subsidence zone have also observed elevated deformation magnitudes within (towards the mine) from the most significant bounding structure. Select findings have been presented previously in Kamp et al. (2020). Instrumentation data are shown in Figure 13 and key findings include:
  - The TDR cable clipped by September 2019 within a known fault zone at approximately 42 m along the drillhole (mAH). The clip location corresponds with the limit of higher deformations

observed on surface and timing of the clipping corresponds with relatively high West Cave mining rates.

- ○ MPBX anchors installed within the boundary between approximately 40 and 50 mAH monitored significant extensional deformation (approximately 80 mm towards the subsidence zone) during 2019 and 2020, while West Cave remained active.
- ○ Geo4Sight Markers installed within the structural boundary (approximately 40 to 50 mAH) experienced elevated angular deformation rates from August 2019 through January 2021, while West Cave mining was active. Observed angular deformation rates are clearly linked to West Cave tonnage, as illustrated previously on Figure 10.

Figure 11 Photograph of surface expressions associated with the northern structural boundary near the vent raise infrastructure

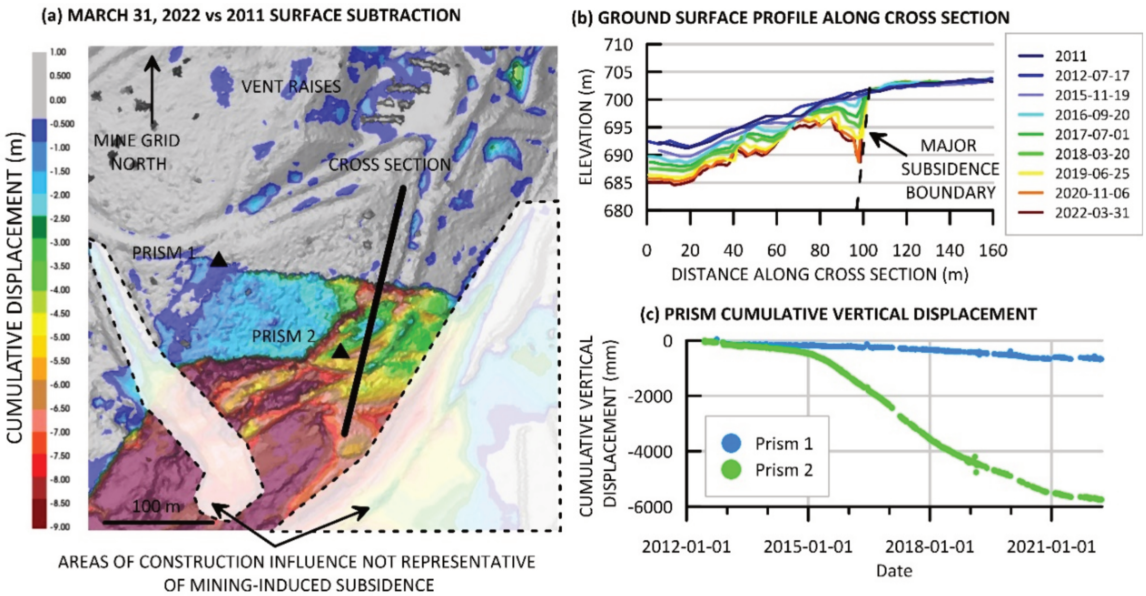

Figure 12 Contrasting surface deformation magnitudes across the northern structural boundary near the vent raises

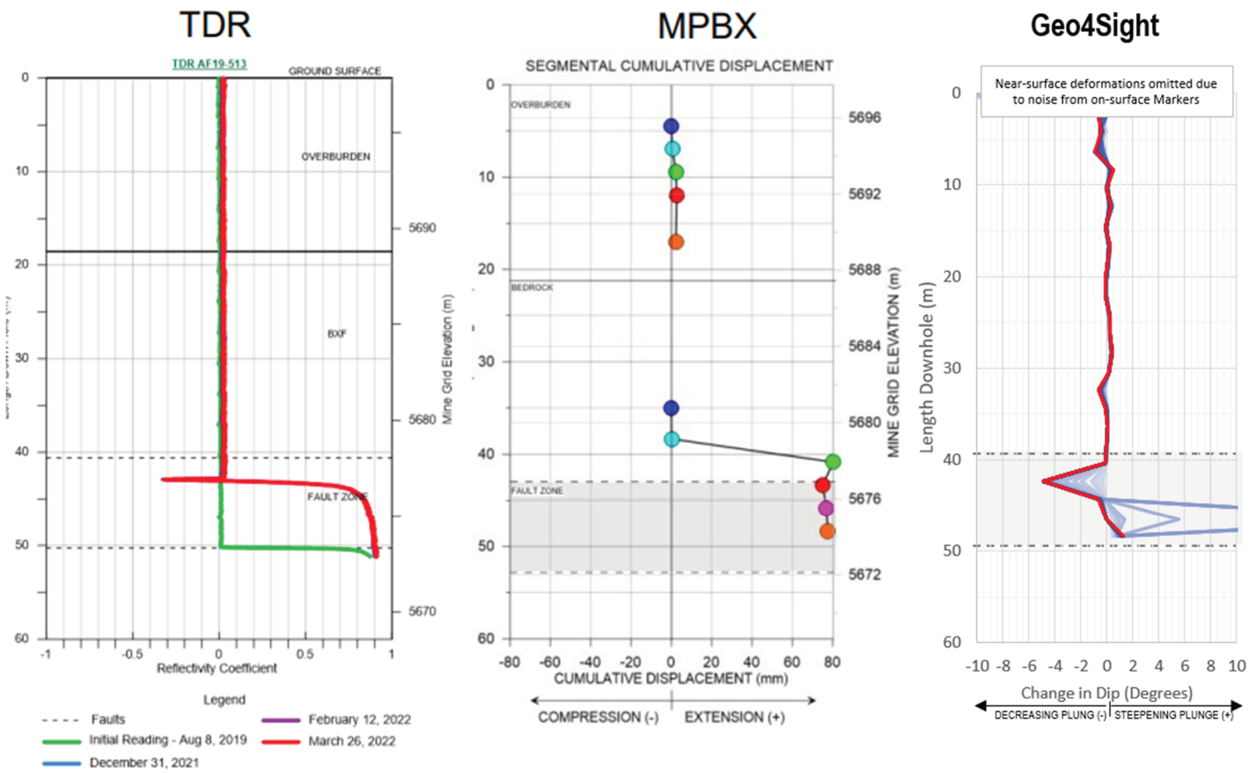

Figure 13 Elevated subsurface displacements observed near vent raise within northern structural boundary by TDR, MPBX and Geo4Sight instrumentation (updated from Kamp 2020)

Major subsidence boundaries have developed between the New Afton TSF and the Lift 1 footprint, along the southern boundary, that have resulted in a similar limiting effect on observed subsidence extent and magnitudes. Deformation magnitudes monitored using photogrammetry on both sides of this structure are shown on Figure 14. Contrasting deformation magnitudes have been observed across the boundary, which began to manifest in 2017, coinciding with increasing draw and subsidence influence from the East Cave. Cumulative vertical deformations observed outside the structure (towards the New Afton TSF) between September 2016 and March 2022 remained below the experiential detection limit (approximately 0.7 m), while those observed within the structure range from approximately 10 to 35 m. The progression of the subsiding ground surface within the structure follows a 'stepped' profile with both vertical and horizontal components of movement; downwards and towards the Lift 1 footprint, as shown in Figure 14. This behaviour suggests a toppling kinematic mode along sequential steeply dipping structures subparallel to the orebody within the Nicola Group bedrock unit, with the movements in the overlying till and waste rock units responding to this mechanism (Davies et al. 2018; Kamp et al. 2020). The magnitude of the horizontal component of movement is likely influenced by the south pit slope deformations (discussed further in Section 5.3).

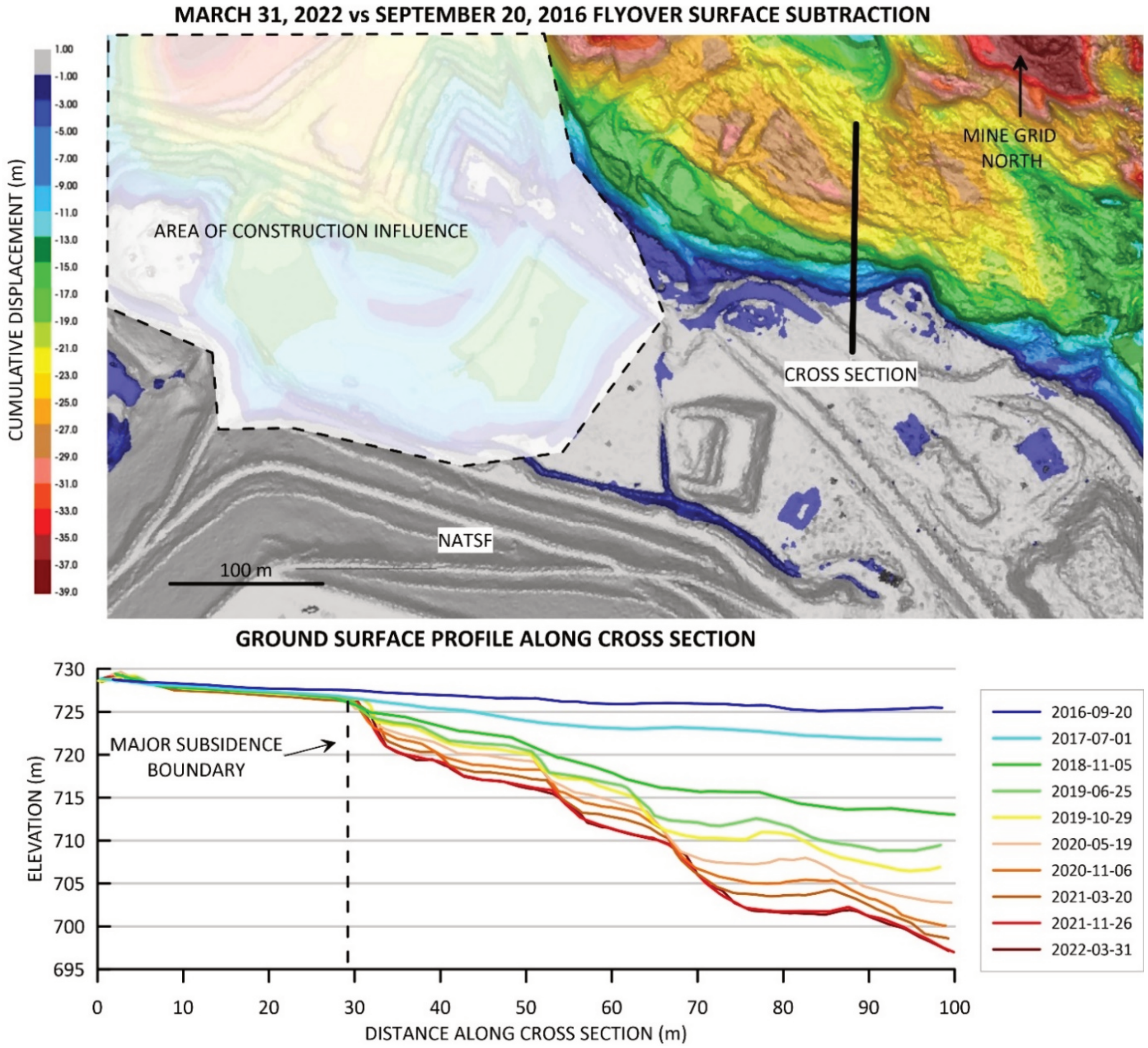

Figure 14 Contrasting deformation magnitudes across structural boundary near the NATSF

5.3 Block cave interaction with the historical Afton Pit

The Lift 1 footprint extends partially below the historical Afton Pit and subsidence has deformed the pit walls, predominantly in response to nearby East Cave mining. Pit geology has resulted in complex and diverse deformation behaviour within the various pit sectors. Major throughgoing faults corresponding with lithological boundaries are dominant controls on pit slope stability and deformations (Stewart & Reid 1988). Afton Pit ground displacements due to subsidence have generally occurred within the Nicola Group volcanic units (BXF). Significant slope deformations have been observed within the south and west pit walls, the mechanisms of which are influenced by their geological characteristics and pre-existing slope instabilities. Observations and mechanisms of deformation are discussed for these slopes in the following sections. Deformations of the northeast pit slope within the Volcanic and Sedimentary sequence (ES) have remained small and those observed within the southeast pit slope within the diorite (DI) are negligible. These slopes exhibit comparably better rock characteristics and are in areas where only minor subsidence influence has occurred.

Pit wall deformations monitored using terrestrial LiDAR change detection within the south and west pit slopes between February 18, 2022 and May 2, 2018 are shown on Figure 15. Deforming ground surface profiles developed from the LiDAR and UAV flyovers along cross sections through the south wall (cross-section A-A’) and west wall (cross-section B-B’) are provided for the period between June 2014 and March 2022. The condition of the south and west pit slopes in April 2022 is shown on Figure 16.

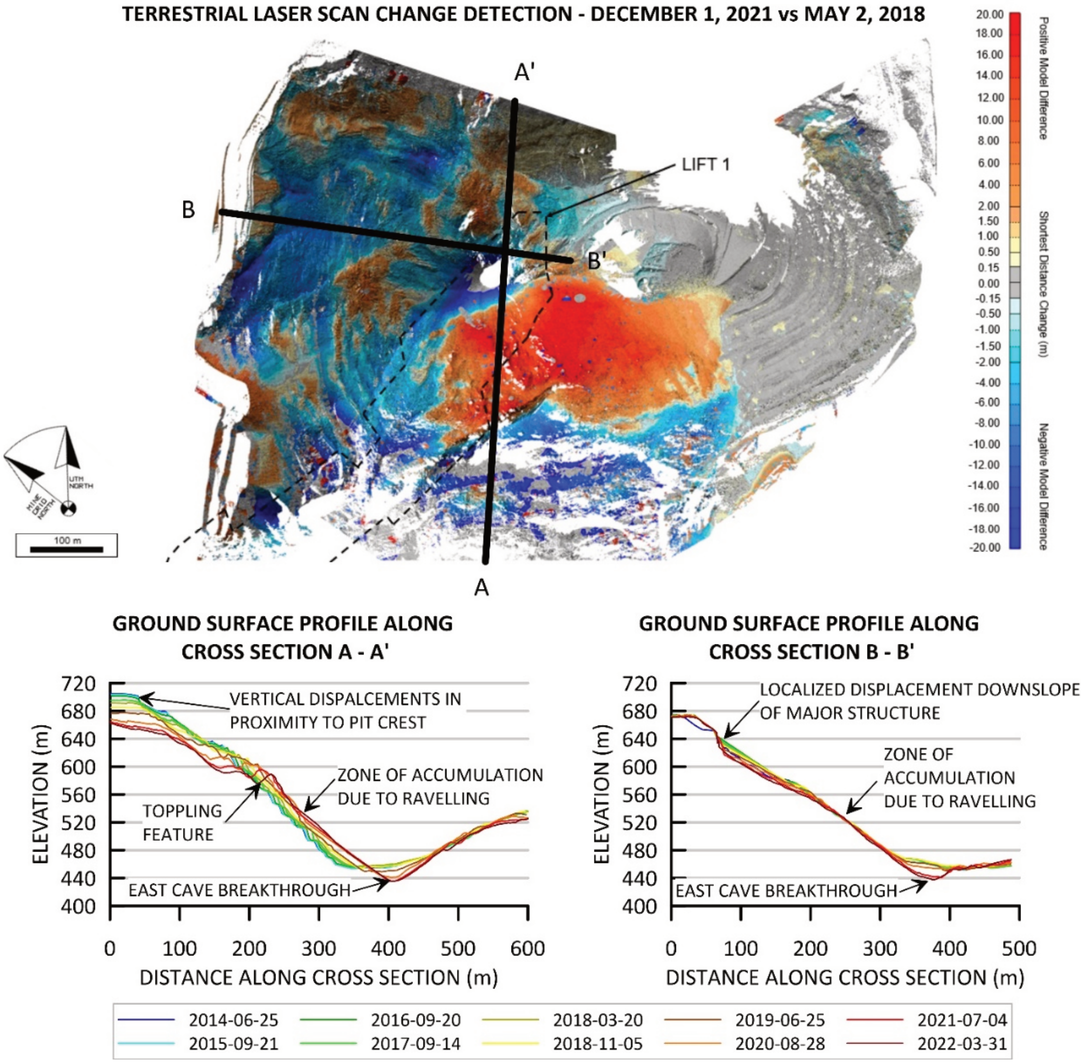

Figure 15 LiDAR monitored Afton Pit wall deformations show toppling and accumulation (Section A-A’) and deformation influenced by major geological structures (Section B-B’)

Figure 16 Afton Pit wall deformation features and major geological structures (looking west)

The south pit wall used to be the most stable part of the pit during initial historical mining of the Afton Pit (during the 1970s and early 1980s). As mining continued, cracking and increased slope displacements were observed and a toppling failure of approximately 7.3 million tons occurred in June of 1986 (Reid & Stewart 1986). Displacement of the south wall has continued along the pre-existing toppling structures as block cave mining has resulted in subsidence at the toe. The following observations of south wall behaviour can be drawn from Figures 15 and 16:

- The south pit slope has generally exhibited bulging and ravelling behaviour driven by subsidence.
- Increased displacement rates in the south wall occurred as mining shifted into East Cave, resulting in slope ravelling due to progressive over-steepening resulting from mine subsidence near the toe.
- A major toppling structure (at an approximate elevation of 580 m) acts as a transition between downward vertical displacement at and above the pit crest and accumulation of material (positive topographical change) from ravelling towards the toe.
- Mainly vertical subsidence deformations are observed within the western part of the south slope, where the toppling structure is no longer exposed due to the change in pit wall azimuth.
- There is a sharp limit to the displacement extent at the eastern side of the south pit slope correspondent with the interpreted contact between the BXF and the diorite lithological units.

Deformation of the west pit slope is predominantly vertical and exhibits large deformation offsets (step changes) across sub-vertical cross faults. These faults are interpreted to be truncated by the tertiary sediments to the northeast, limiting the extent of the complex deformation behaviour observed along these structures. The following observations of the west wall behaviour can be drawn from Figures 15 and 16:

- Zones of accumulation (positive topographical change) from ravelling exist on the down-slope side of major structures that crosscut the west pit slope.
- Approximately 35 m of localised, predominantly vertical, displacement has occurred along the major structure in the upper part of the slope, below the waste rock dump.

Initial pit wall monitoring data following East Cave closure (February 2022) indicate that deformations within the pit walls are slowing with time following conclusion of mining, as anticipated. This finding has been observed using prisms located along the pit crest and along the north access road and is apparent in remote sensing data.

6 Summary

Subsidence deformations resulting from Lift 1 mining have been rigorously monitored and evaluated due to the presence of surface infrastructure, including TSFs, in proximity to the mining area. The monitoring program at New Afton is substantial and deformations (both surface and subsurface) are monitored using an extensive network of in situ instrumentation and by remote sensing techniques. Data from multiple monitoring techniques allow for cross-verification of findings between methods. Recent additions to the subsidence monitoring network are at the forefront of geotechnical instrumentation technology and include Elexon Geo4Sight Markers, ground-based slope stability radar, and satellite inSAR.

Lift 1 mining at New Afton began in 2011 and subsidence was first monitored onsite following breakthrough (initial surface deformation) of West Cave to surface in February 2013. The initial breakthrough location was offset from the West Cave footprint due to interpreted influences from the weaker picrite rock mass and presence of historical waste rock, which are inferred to have resulted in a southwestward 'lean' as the West Cave propagated to surface. The extent of subsidence and the spatial distribution of subsidence rates are influenced predominately by the rate and spatial distribution of production draw and the geological environment (i.e. rock mass characteristics, structural geology). Monitored surface and near-surface deformation rates were highly reactive to increasing or decreasing tonnage and the shift of production from West Cave to East Cave as Lift 1 mining progressed. Surface and subsurface displacements have been observed to be constrained by the existence of bounding structural features (faults and lithological contacts), which have limited the expansion of subsidence within several areas, notably within the southern boundary downstream of the TSFs and northern boundary near the vent raises. The Lift 1 footprint extends partially beneath the historical Afton open pit and the observed subsidence behaviour within the various pit sectors is complex and diverse depending on geology and pre-existing pit wall instabilities within the pit from historical mining. Initial monitoring data following the conclusion of Lift 1 mining indicate that deformations have begun to slow across the subsidence zone, including within the Afton Pit, as expected.

Acknowledgement

The ability to so comprehensively monitor the progression of subsidence would not be possible without the significant effort and commitment of New Afton to implement an extensive state-of-the art monitoring network and the commitment of New Gold staff to maintain exacting data collection practices and keep all systems functioning. The authors acknowledge the contribution of a large number of individuals in many roles in this collaborative effort between New Gold, Knight Piésold, and BGC Engineering.

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