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Smart technology for monitoring caving subsidence

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Abstract

Caving mining methods cause significant deformation and subsidence of the ground surface. Development and surface infrastructure is typically situated close to the mining area in order to optimise production paths. However, detailed knowledge of subsidence limits only becomes available as mining advances. Therefore, it is critical to monitor the evolution of subsidence in order to mitigate adverse safety and economic impacts. A network of surface and underground instruments is vital for such monitoring. Traditional monitoring methods include surface scanning in combination with subsurface instrumentation. Many subsurface instruments rely on physical connectivity but this can be lost due to the large deformations typical of mining subsidence. This paper presents the preliminary results of a trial of Elexon Mining's Geo4Sight networked markers coupled with conventional instrumentation to monitor caving subsidence at the New Afton Mine.

1 Introduction

New Afton is a copper-gold porphyry deposit block cave mine located 8 km west of Kamloops, British Columbia, Canada. Pre-production underground development occurred between 2007 and 2012 while undercutting of the West Cave, about 600 m below the surface, started in May 2011. The first drawbell was completed in September 2011 and mill production commenced in 2012. Following an aggressive ramp-up and drawbell schedule, deformation was seen on the surface in February 2013. Cave breakthrough was verified by drone and surface prism surveying and, later, by back analysis of micro-seismic data.

To enhance the existing monitoring network and monitor deformations in the vicinity of important surface infrastructure, New Gold Inc. (New Gold) worked with SRK Consulting, Canada, to conduct a trial of the Geo4Sight networked instruments (termed 'markers') produced by Elexon Mining Pty. Ltd. (Elexon Mining). The markers were installed alongside time-domain reflectometry (TDR) and multipoint borehole extensometer (MPBX) instruments to permit data comparison with conventional instruments. The New Afton trial follows trials with earlier versions of markers at the Mina Sur mine (Chile) (Teuber 2016) and the Highland Valley Copper (HVC) Mine (BC, Canada) (Beingessner et al. 2020).

2 Background

This section describes the New Afton subsidence monitoring network, discussing the limitations of conventional instruments and how wireless technology was used to complement the network.

2.1 Subsidence profile

Surface expression of the subsidence propagated outwards from the crater asymmetrically. The furthest surface cracking is to the south and the limits are curvilinear (Figure 1). This zone is generally aligned with the long axis of the cave footprint and its southern extent is coincident with the location of a weak rock unit.

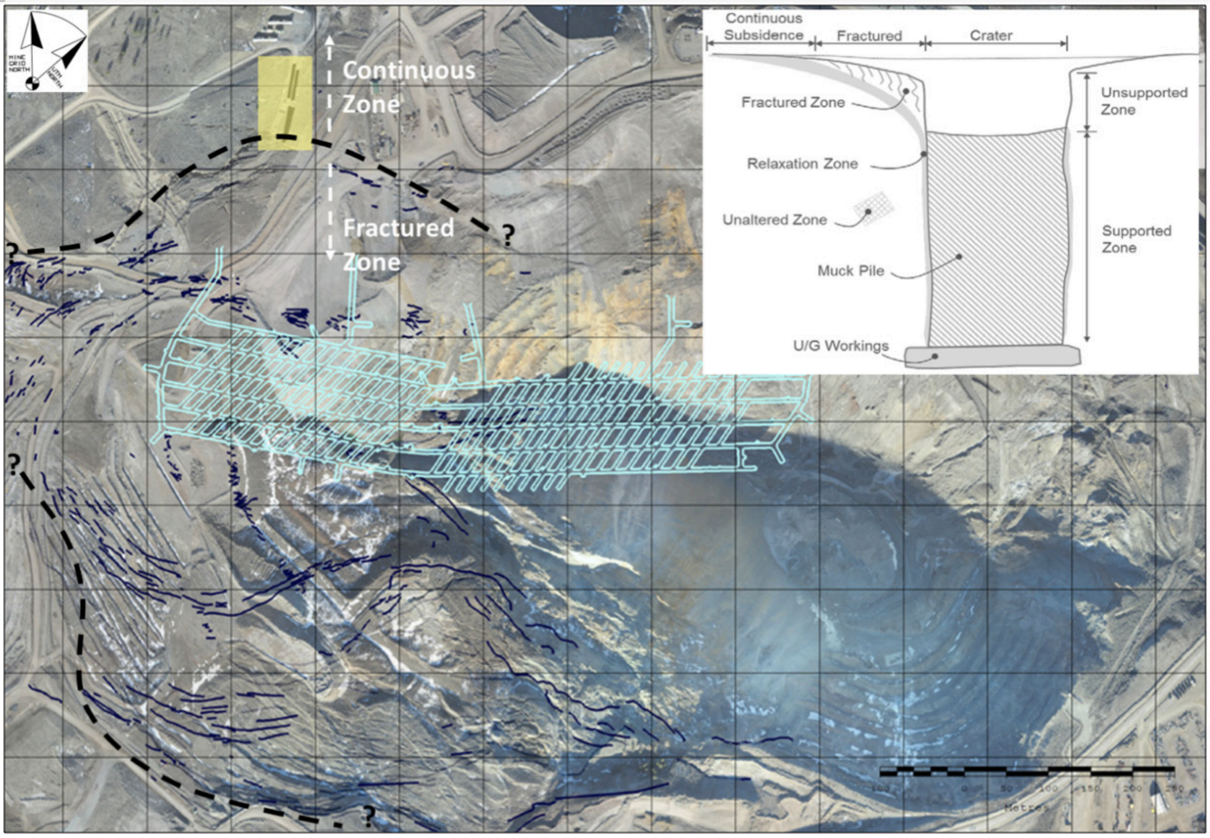

Figure 1 **Plan view aerial image showing projections of the West and East Cave footprints at about 600 m depth and geometrical crack correlation patterns (dark blue lines) on the surface. The yellow rectangle is the Geo4Sight trial area. Inset is a schematic of a typical subsidence profile and the terminology**

Monitoring data indicated that the subsidence grew predominantly south of the cave footprint. This is expressed on the surface as radial patterns of tension cracks and scarps. To the north, the subsidence is also expressed as scarps and tension cracks, but is truncated sharply. The control on this limit is interpreted as associated with a steeply dipping major structure and lithological contact.

2.2 Existing monitoring network

New Gold has installed instruments in several programs since 2011. The first program was completed during 2011 and 2012 and captured pre-production to steady-state cave propagation. The objective of this program was to have an automated system for monitoring cave growth and propagation to the surface. It included TDRs, a micro-seismic system, crack mapping, annual flyover scans and survey prisms monitored by a robotic total station. The system was expanded in subsequent programs and now consists of:

- Survey prisms: Read daily to provide 3D surface displacement data
- Survey monuments: Typically surveyed bi-weekly using DGPS to record 3D surface displacement data outside the line of sight of the total station
- Crack extensometers: Two pins installed at each crack location and surveyed monthly using DGPS to track displacement and measure the 3D displacement of cracking
- Drone flyover point cloud data: One flyover per month to measure vertical elevation changes due to subsidence and observe surface earthworks
- Time domain reflectometry cables: With locations consisting of standalone installations or coupled with MPBXs, inclinometers or Geo4Sight markers; TDRs are on an automated system that is read daily

- Slope inclinometers: Many slope inclinometers nested with settlement magnets, read every six weeks, to monitor horizontal displacements at various points along the borehole and vertical displacement where magnets are installed
- Multipoint borehole extensometers: To monitor displacement location ranges and magnitude, automated and read daily
- Settlement plates: To monitor surface settlement
- Vibrating wire soil extensometers (VWSE): To monitor displacement
- Groundwater monitoring with vibrating wire piezometer and standpipe piezometers: To monitor groundwater elevations
- Geo4Sight markers: four holes coupled with MPBX and TDR cables.

2.3 Limitations of traditional instruments

Traditional subsurface instrumentation, such as inclinometers and TDRs, rely on the physical connectivity of casing or wires to remain functional. New Afton has experienced the following limitations/challenges associated with conventional instruments:

- Short lifespans for those closest to the crater where there are large deformations. In several cases, the inclinometer casing was sheared or deflection limits exceeded shortly after installation. TDRs are also susceptible to damage from large deformations and are no longer useful if the cable is sheared near the collar.
- Practical limitations on the total depth of installation of inclinometers due to the risks of collapsing drillholes. In some cases, TDRs were extended deeper by installing through the drill rods, but this entails the risk of being cut when pulling the rods.
- Restriction on the angle of installation by instrument serviceability requirements. Inclinometers are essentially constrained to vertical drillholes and TDRs are challenging to install in deep holes.
- Inaccessibility to some instruments closest to the crater for safety reasons.

Overcoming these limitations would make the monitoring network more robust and lead to overall cost and time savings.

2.4 Geo4Sight markers

Although the existing network is comprehensive, Geo4Sight markers were trialled to supplement it with:

- Monitoring that is not dependent on physical connectivity between measurement points;
- The ability to inform characterisation of deformation mechanisms and directions;
- Remote acquisition of data in real-time or customised time-intervals.

Geo4Sight markers are rugged battery-powered devices that can transmit signals up to about 5 m through the ground. Depending on battery demand, they can have an operating life of up to ten years. The markers are currently available in two configurations: i) tilt, and ii) tilt and pore pressure.

They are typically installed downhole in a string with sensors installed every 2 m and grouted in place. Data is transferred to the surface from marker-to-marker using radio telemetry. They are interrogated by a datalogger at the collar, which communicates with the marker closest to the surface. Data is then forwarded to the next marker and so on until the communication reaches the destination marker. The destination marker takes measurements and sends the data back to the logger (Figure 2). In this manner, all markers can be queried. Geo4Sight tilt markers measure a heading and dip orientation, pitch, roll and received signal strength. These measurements permit interpretation of the angular deformation profile. The tilt sensitivity of the markers is 0.02 degrees (standard specification).

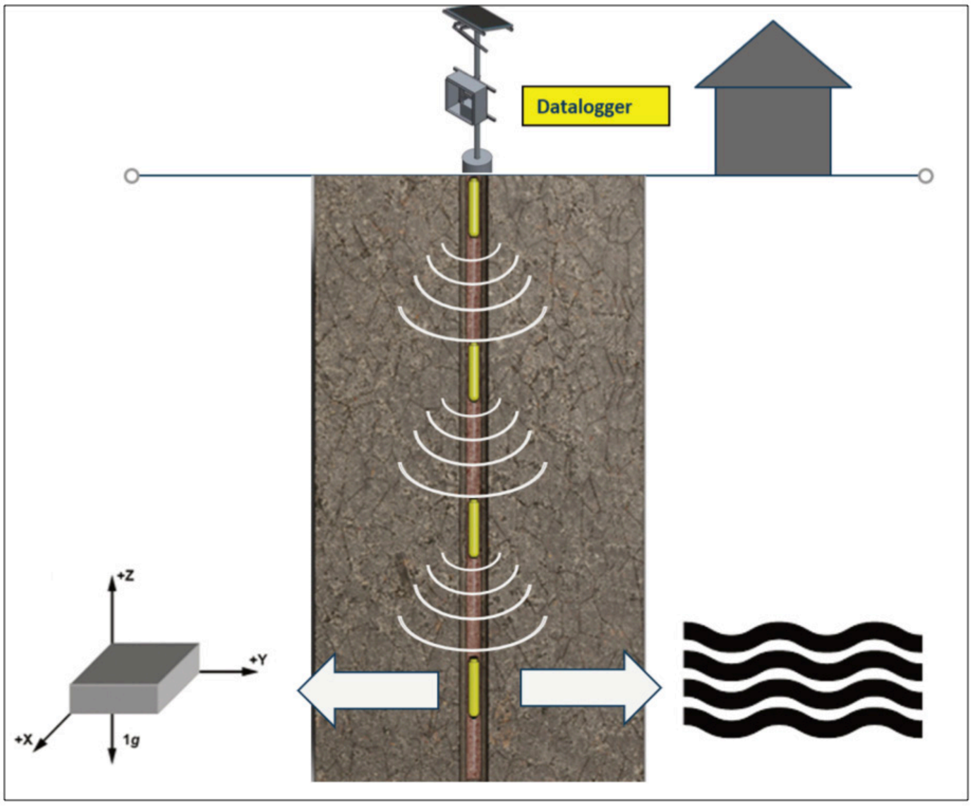

Figure 2 **Configuration and components of the Geo4Sight system**

3 Geo4Sight trial

This section describes the specifics of the trial site and installation approach.

3.1 Site

The Geo4Sight trial installation area is on the northern side of the subsidence zone. As shown in Figure 3, the ground has subsided and this is expressed on the surface as tension cracks and scarps.

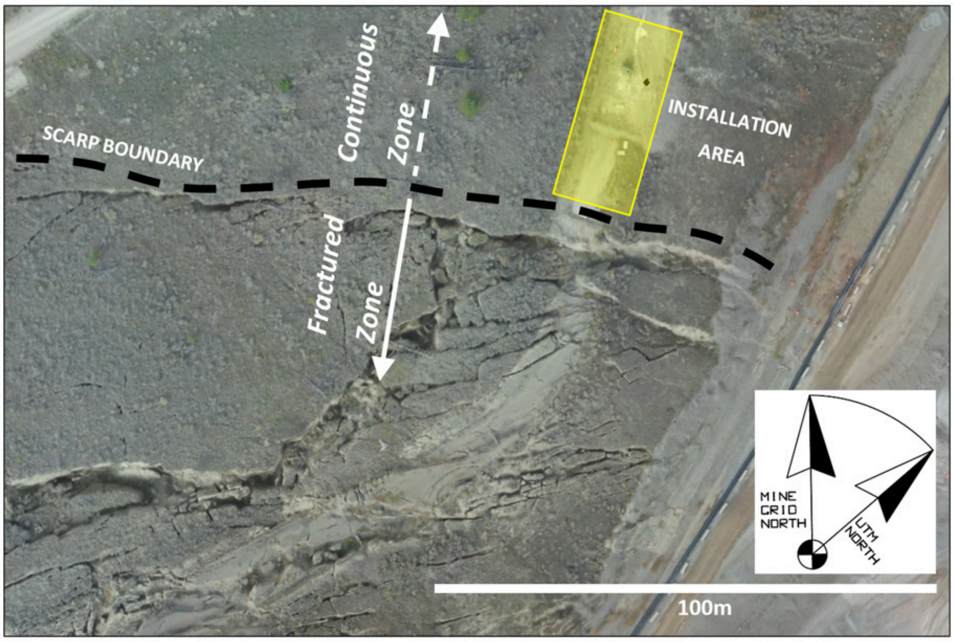

Figure 3 **Aerial image showing the active zone boundary and Geo4Sight installation area (in yellow)**

There is a truncated boundary between the subsidence fractured zone and the more stable ground of the continuous zone to the north. This area has been monitored via visual inspections and surface survey methods since 2012. The data shows that the magnitude and intensity of surface cracking have increased, but the boundary location has been relatively static. This has resulted in the formation of a scarp, with less than 0.5 m of vertical subsidence in the continuous zone and over 8 m of vertical subsidence in the fractured zone (Figure 4). The failure mechanisms of the overburden appear to be both circular rotation and toppling. Figure 4 shows the fractured zone and an early conceptual representation of the failure mechanisms.

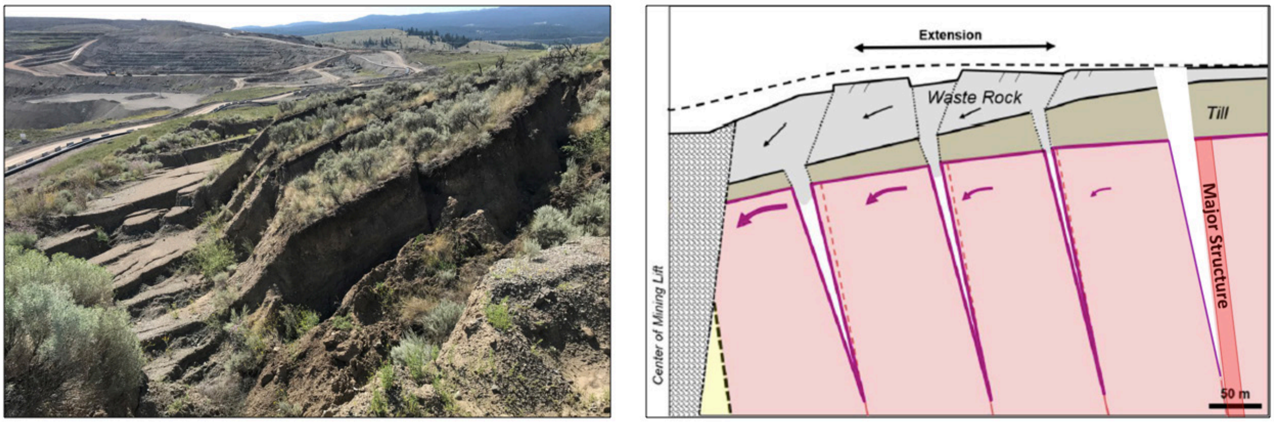

Figure 4 Left: Photo looking south (mine grid) of the fractured zone taken from the boundary; Right: Conceptual representation of the local failure mechanisms, overburden extending in response to underlying bedrock movement (modified after Davies et al. 2018)

3.2 Installation

SRK worked with New Afton and Elexon Mining to carefully design the installation method. Six inclined holes with a length of up to 53 m were drilled in pairs using the PQ diamond coring technique and the core was collected and logged. Each hole was drilled and completed consecutively. The instruments were laid out on the surface and attached to PVC pipe strings to: i) accurately position them down the hole, and ii) support a grouting tube (Figure 5). The completed strings were fed through the drill string and drill rods were pulled in segments as the annulus was filled with grout in batches. Grouting was completed using the fully grouted method (Mikkelsen & Green 2003) with a grout mix designed for strength compatibility with the surrounds.

Figure 5 Preparation of the instrumentation string on surface (left) and description of the components (right)

Geo4Sight tilt markers, MPBXs and TDRs were installed together in three of the holes. The fourth hole (AF19-004) included only Geo4Sight markers and TDRs. Geo4Sight markers and MPBXs are complementary systems as they measure rock mass deformations in different axes: Geo4Sight markers measure angular deformation perpendicular to the hole axis while MPBXs measure deformation (extension or compression) along the axis. The Geo4Sight datalogger servicing all holes was installed in a monitoring hut at the collars. The datalogger was connected to the mine system via a fixed network cable. Drillhole and instrumentation details are shown in Figure 6 and summarised in Table 1.

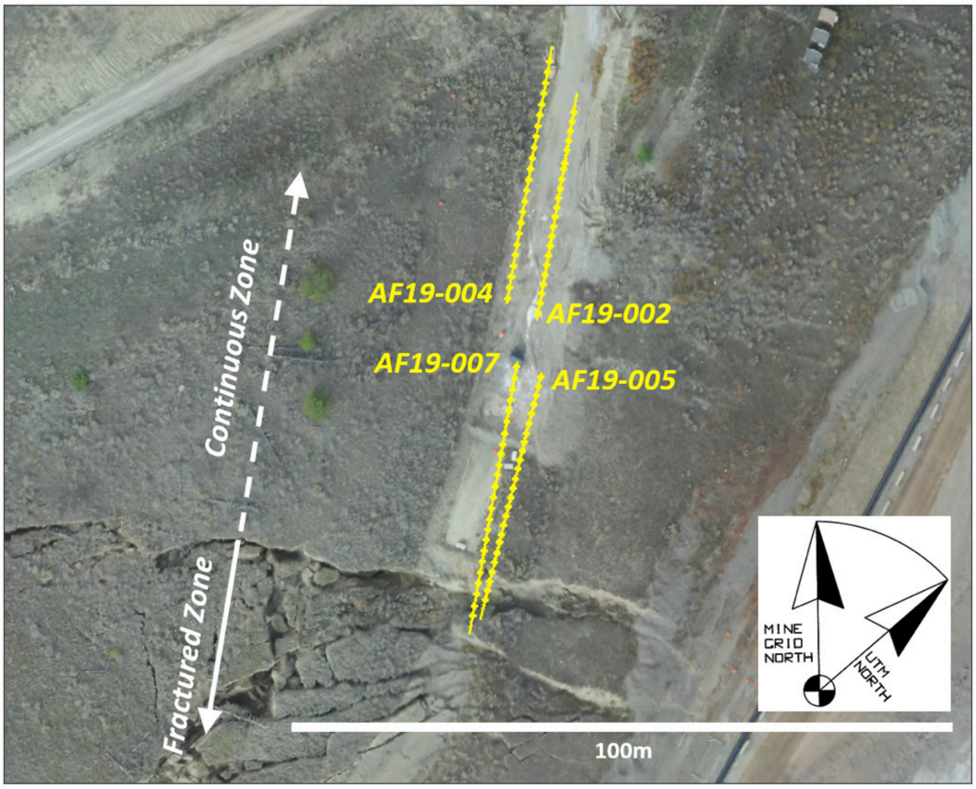

Figure 6 Aerial image showing traces of instrumentation holes with TDRs, MPBXs and Geo4Sight markers

Table 1 Drillhole and instrument details

Drillhole							Instruments
ID	Easting[1] (m)	Northing (m)[1]	Elevation (m)[1]	Length (m ADH)[2]	Dip (°)[1]	Azimuth (°)[1]	
AF19-002	**3372.7**	**2382.7**	**5697.9**	**47.3**	**-39**	**010**	**Geo4Sight (22), MPBX (3x6 anchor), TDR**
AF19-004	3367.8	2385.3	5698.1	47.7	-29	010	Geo4Sight (23), TDR
AF19-005	3373.4	2374.2	5697.7	53.2	-40	194	Geo4Sight (25), MPBX (3x6 anchor), TDR
AF19-007	3369.5	2375.9	5697.7	50.3	-29	190	Geo4Sight (24), MPBX (3x6 anchor), TDR

[1] New Afton Mine Grid; [2] ADH = along drillhole

4 Preliminary Geo4Sight results

This section presents preliminary data from one of the drillhole installations (AF19-007) for which Geo4Sight, MPBX and TDR data are available.

After the installation, manual baseline readings were taken from all the instruments and the process began to connect them to the network. Over the time taken to connect to the network some deformation was not captured. Once the system was automated and regularly reading, all instrumentation types in AF19-007 (TDR, MPBX and Geo4Sight markers) showed deformation throughout the hole. Significant deformation was observed at the end of the hole within the faulted rock mass from around -40m to -50m. This relatively high deformation interval is interpreted to be within a major structure associated with subsidence shear and topping failures observed on surface (Figure 7). The TDR cable was sheared within this fractured zone at -42.23 m. TDR data collection of the sheared location is no longer possible; however, the MPBX and Geo4Sight markers remain connected and collecting data within the fractured zone.

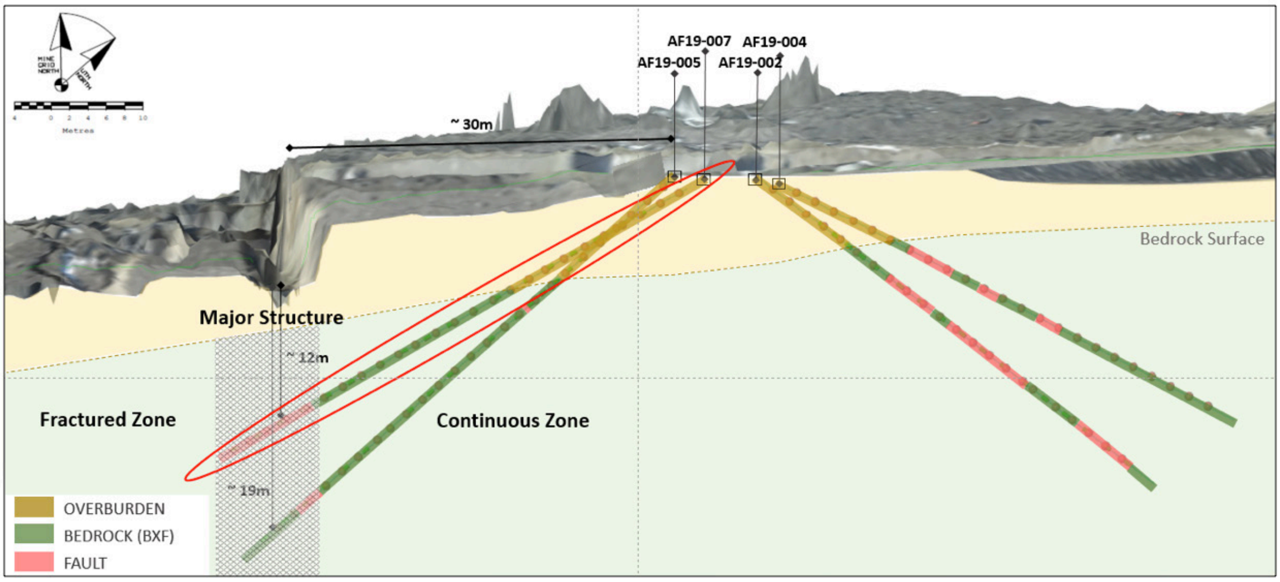

Figure 7 Section view looking southwest of monitoring holes and the fractured and continuous subsidence zones; the hole (AF19-007) of interest is circled and spheres indicate the Geo4Sight markers

Data from all the AF19-007 instruments is plotted in Figure 8. Geo4Sight data is represented by plotting change in dip and heading angles relative to the post-installation baseline readings. The Geo4Sight dip angle (degrees) is measured between the gravitational vertical and the marker x-axis (along the long axis of the marker). The Geo4Sight heading angle (degrees) is measured counter-clockwise (CCW) between magnetic north and the plan-view projection of the marker's x-axis. Heading data may be thought of as the CCW positive azimuth relative to magnetic north. MPBX data was resolved to cumulative displacement measurements (mm) and the TDR data is represented as a cut when the reflectivity coefficient shows the end of cable.

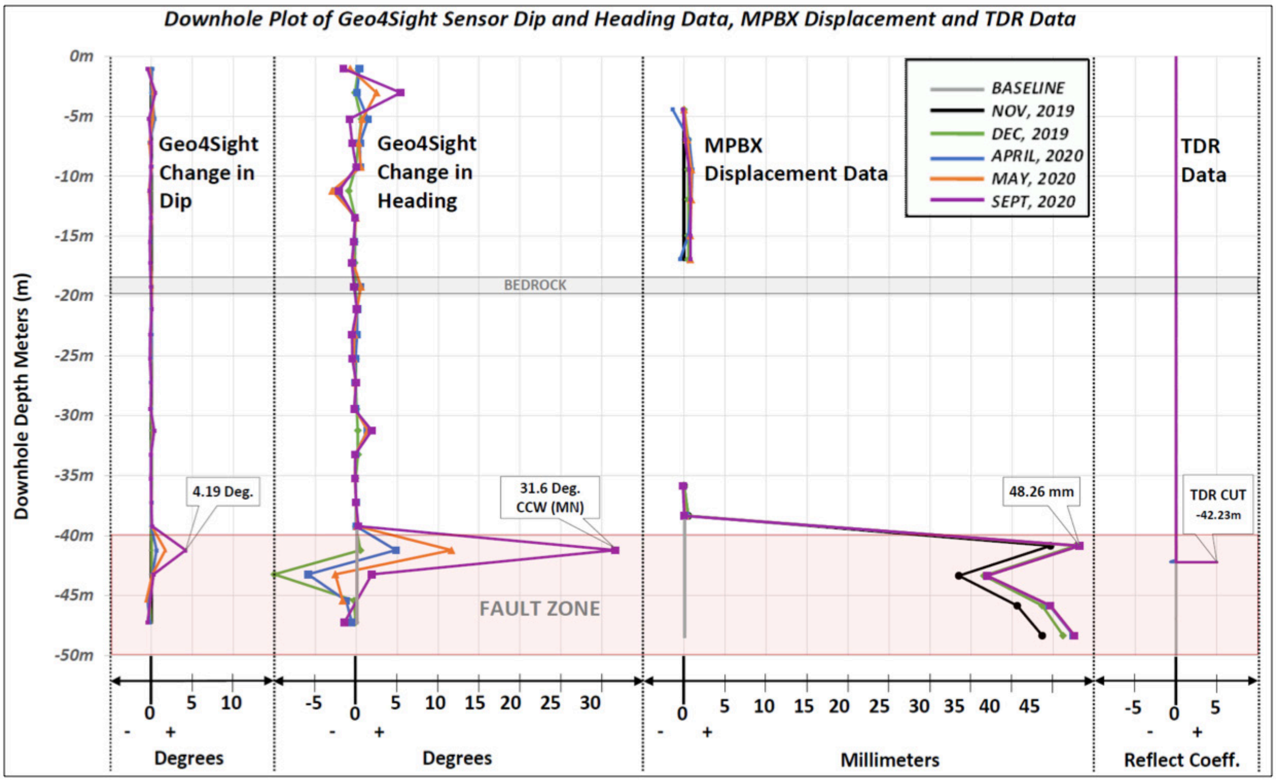

Figure 8 Summary of data from all instrument types: Geo4Sight change in dip and change in heading, MPBX cumulative displacement and TDR data

Plotting the heading angle orientation from the most displaced Geo4Sight marker (located at -40.8 m) within the fault zone provides a time-series of plan-view deformation direction relative to magnetic north (translated to mine grid north). The results indicate that the displacement within the fault zone was initially perpendicular to the strike of the major structure followed by an azimuth change to the southeast (Figure 9). This is moving towards the direction of the extraction level (Figure 10), indicating material movement towards the subsidence crater. The change in dip also indicates that the marker at -40.8 m has steepened over time along its x-axis.

Compiling the heading orientation and dip angle data provided by the Geo4Sight marker at -40.8 m with axial deformation data from the MPBXs permits triangulation of a subsurface deformation vector. Displacement data from the MPBXs indicates an extensional displacement of 0.048 m. Geo4Sight heading and dip data can be combined to orientate the MPBX axial displacement magnitude at depth. In this case, the data suggests that the axial displacement vector is oriented at the heading (i.e. azimuth) of 159° with a dip (from horizontal) of approximately 33° (drillhole dip plus change in Geo4Sight dip angle). A nearby surface prism within the fractured zone indicates a similar heading direction to that measured by the Geo4Sight marker (Figure 10). Furthermore, there is an indication that the near-surface displacement rate is higher than the sub-surface rate -40.8 m down hole of AF19-007, which aligns with the extension failure conceptual model (Figure 4).

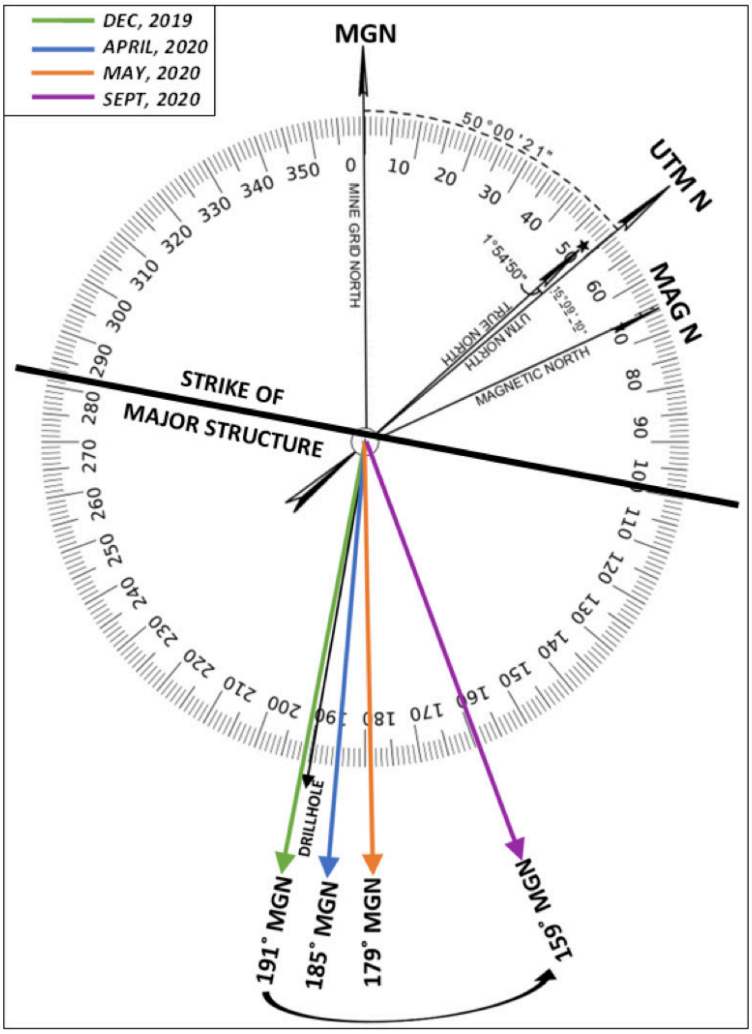

Figure 9 Geo4Sight heading orientation over time in AF19-007 at -40.8 m down hole, heading data relative to mine grid north within the fault zone; later movement is towards the direction of the active extraction area (subsidence crater)

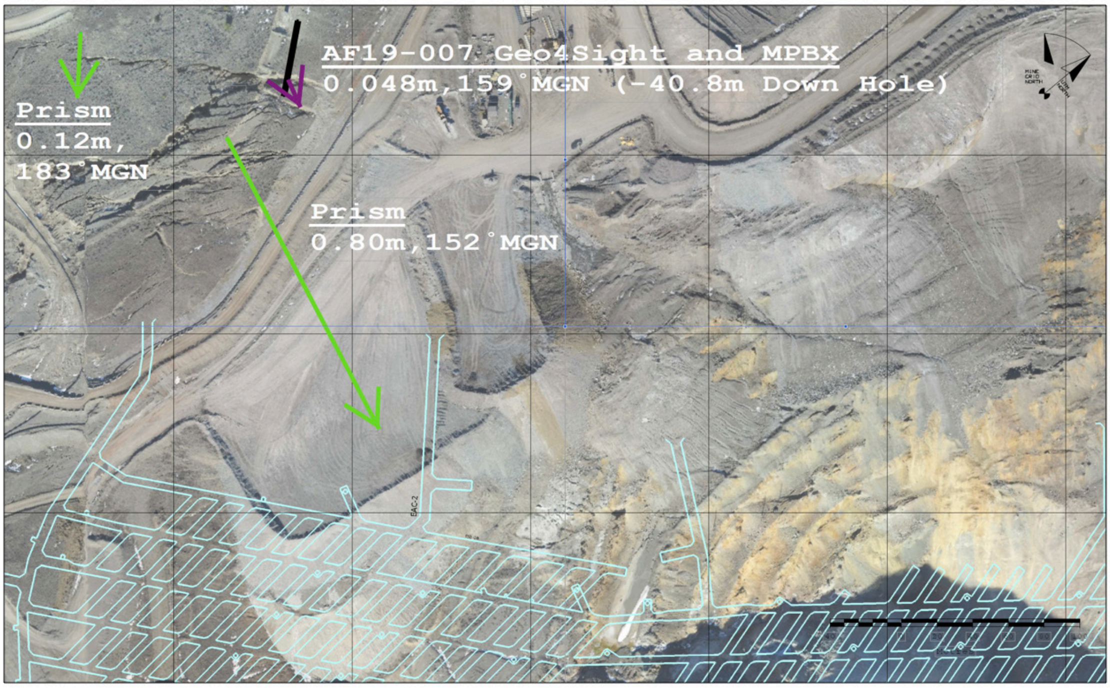

Figure 10 Nearby prism displacement vector (exaggerated scale) taken from Dec 2019 to Sept 2020 showing the same trend as the Geo4Sight marker at -40.8 m; both are moving towards the mining subsidence crater

5 Discussion and conclusions

When correctly installed and set up, Geo4Sight markers can permit downhole angular deformation monitoring through measurement of dip and heading angles. These measurements are complementary to those using MPBX instrumentation, which monitors axial displacement. By compiling this data, a ground deformation displacement vector at depth can be constructed.

The observed changes in the Geo4Sight and MPBX instrumentation over time may permit measurement of directional changes in deformation at depth. This can lead to a better understanding of failure mechanisms that may be beyond the capabilities of traditional instrumentation due to the magnitude of the deformations.

The results of the analysis for this specific location have been used to validate that extensional cracking on the surface (measured using the prisms and flyovers) and at depth (measured using the Geo4Sight markers and MPBXs) is moving towards the area of the mining subsidence crater.

The subsidence monitoring data obtained since 2011 has been invaluable in understanding failure mechanisms and subsidence progression. The data obtained from the various instruments and its subsequent analysis have been incorporated into trigger action response plans (TARPs) and used to calibrate subsidence models.

Within the trial area, there is currently a good correlation between all the instruments installed to observe subsidence-related ground deformation. New Afton is planning to continue installing traditional instrumentation as a primary system coupled with Geo4Sight markers in selected active subsidence areas.

Note

Since the writing of this paper, Elexon has changed the heading data reference to clockwise (CW).

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