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Observed cave flow behaviour at the Argyle block cave and its implications for cave performance

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Abstract

The Argyle Diamond Mine (ADM) block cave was the first cave mine to deploy a cave-scale active Cave Tracker System, complemented by passive flow markers and surface observations. These marker systems were installed to better understand cave flow behaviour in a geologically complex orebody, and to assess the practical requirements and limitations associated with cave flow monitoring technologies so that they could be successfully deployed at the Oyu Tolgoi block cave mine. This paper documents the installation approaches, operational performance, and data recovery of the Cave Tracker System and associated flow markers implemented at ADM.

The cave tracker results, recovered markers, and surface breakthrough observations collectively indicated a predominantly isolated draw behaviour, characterised by limited lateral interaction between adjacent drawpoints. Notable examples included beacons exhibiting strongly channelised vertical movement consistent with tight drawcone formation, while others demonstrated significant lateral displacement, potentially indicative of rilling mechanisms within the caved column. These observations provided direct insight into cave flow processes and highlighted the sensitivity of cave behaviour to draw strategy and cave geometry. The ADM experience offers an important early reference case for cave flow monitoring, demonstrating how integrated flow measurements can be used to improve interpretation of cave mechanics and to inform draw management strategies in future large-scale block cave operations.

Keywords: *cave flow, cave flow monitoring, isolated draw, drawcone, rilling, block cave*

1 Introduction

The Argyle Diamond Mine (ADM), operated by Rio Tinto and located in the east Kimberley region of Western Australia, approximately 2,300 km northeast of Perth, was one of the most technically challenging block cave operations in the world. The AK1 lamproite orebody was mined as an open pit from 1985 until transition to underground block cave mining in 2013. The underground block cave, known as the Argyle Diamonds Underground Project, delivered a cave footprint of approximately 480 × 180 m with 236 active drawpoints across the extraction level at approximately 300 m below the pit bottom.

Understanding cave material flow is fundamental to an efficient and safe block cave operation. The ability to distinguish between interactive draw, isolated drawcone formation, and anomalous movement behaviours such as rilling determines the effectiveness of draw scheduling, affects the onset of dilution entry, and achievable extraction ratio. Prior to the ADM trial, direct real-time monitoring of material flow within a caving column had not been previously demonstrated at full production scale. Existing flow marker technologies, including passive dumb markers and battery-powered Smart Markers (Whiteman 2010), could record

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installation and recovery positions but could not capture the time-evolving trajectory of markers through the caved column.

As the primary sponsor of the Mining3–Elexon Cave Tracker System (CTS) development program, Rio Tinto planned to deploy the CTS at the Oyu Tolgoi block cave mine in Mongolia. However, before committing to this significant multimillion-dollar investment, Rio Tinto undertook a full-scale pilot trial at ADM with 3 objectives: validate the operational requirements of CTS installation and commissioning in an operating cave environment, understand the technical and interpretive limitations of the system, and generate real cave flow data to inform draw strategy at ADM and the future monitoring design for Oyu Tolgoi.

This paper presents the outcomes of that trial, describing the instrumentation suite deployed, the installation challenges encountered, the key results and their interpretation, and the implications for cave flow mechanics and draw control practice.

2 Motivation: why Rio Tinto sponsored cave tracker development

Once all drawpoints have been developed, block cave mining is fundamentally a bulk material flow management problem. The draw strategy applied – the sequence, frequency, and relative tonnages drawn from individual, appropriately spaced drawpoints – directly determines whether the cave behaves in an interactive or isolated manner. Interactive draw, wherein gravity flow zones from adjacent drawpoints overlap and merge, promotes mass flow and enables the full column of caved material to contribute to ore recovery. Isolated draw, in contrast, results in narrow vertical drawcones that exhaust prematurely, cause early dilution entry from the cave periphery or from overlying waste material, and leave substantial tonnages stranded as 'dead zone' material between cones.

Rio Tinto's strategic interest in cave flow monitoring arose directly from the operational challenges encountered at ADM. The ADM cave was characterised by a geologically complex, inclined lamproite orebody flanked by competent dolerite and quartzite host rocks, with a cave column ranging from 250 m at the centre to over 700 m at the periphery. Rock temperatures approached 60°C at depth. Progressive drawpoint closures driven by extraction level damage, rehabilitation requirements, and wet muck events reduced the accessible footprint over time, creating draw imbalances that exacerbated isolated flow tendencies. At mine closure, approximately 60% of the planned ore reserve could not be recovered (Stegman et al. 2018). This has been attributed in part to isolated draw behaviour and the inability to load-shed effectively.

A key lesson from ADM was that, without real-time visibility of material movement within the cave, draw control decisions are inherently reactive rather than proactive. Cave flow models can predict flow regime tendencies, but they cannot identify the transition from interactive to isolated behaviour at specific drawpoints in real time. Rio Tinto recognised that the Oyu Tolgoi block P0 cave, with a footprint around 500 × 300 m, a cave column exceeding 1,000 m, and reserves of hundreds of millions of tonnes, could not afford to repeat the poor ADM cave performance.

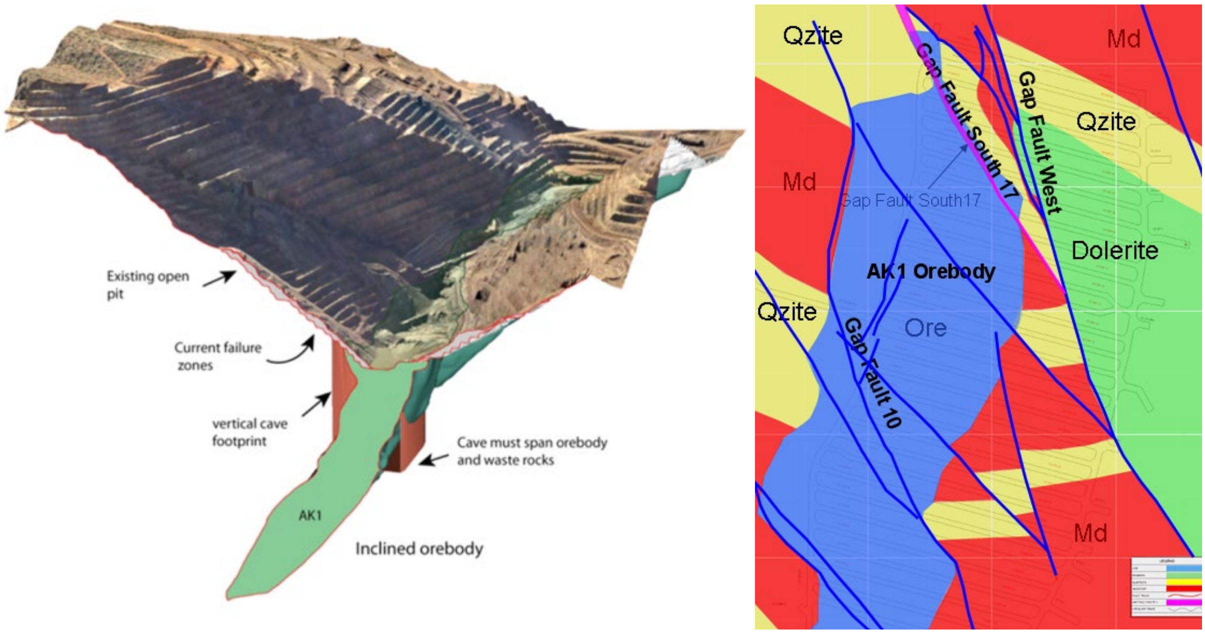
The CTS offered a potential solution: a network of battery-powered beacons installed in the caving column, tracked continuously by fixed electromagnetic detectors, providing time-stamped three-dimensional position data for individual beacons as they migrated downward. This capability would, in principle, allow operators to:

- monitor the geometry and growth rate of the cave back as well as that of individual drawcones in real time
- detect anomalous lateral displacement events indicative of rilling, fault channelling, or other non-gravity-dominated flow mechanisms
- identify developing isolated drawcones before they become irreversible, enabling draw call adjustments to promote interactive flow
- calibrate and validate numerical cave flow models such as REBOP (Rapid Emulation Based on Particle Flow Code) against measured flow trajectories.

The ADM trial was therefore not merely a proof-of-concept exercise but a deliberate investment in the operational knowledge and engineering database required to deploy the CTS effectively at Oyu Tolgoi.

3 Site context and geomechanical setting

The AK1 orebody was a sub-vertical lamproite pipe dipping approximately 75° to the southeast, with intact rock strength (uniaxial compressive strength) of approximately 85 MPa. Surrounding host rocks include dolerite (~66 MPa UCS), quartzite (~104 MPa UCS), and mudstone (~35 MPa UCS), with the weaker mudstone and the structurally significant north–northwest-trending Gap Fault Zone exerting a strong influence on caving behaviour and footprint geometry (Ford 2011). Rock mass rating (RMR_{76}) values ranged from approximately 40 (mudstone) to 59 (quartzite) (Fernandez et al. 2011).



(a) (b)

Figure 1 (a) AK1 inclined orebody, where the cave column must span over waste rock underneath the existing pit; (b) Lithology and fault interpretation at undercut level

The extraction level was positioned at approximately 300 m below the pit floor (approximately sea level), with a drawpoint spacing of 30 × 15 m in an offset herringbone layout. The cave column varied considerably: shorter (~250 m) at the cave margins beneath the pit floor and approaching 700 m at the deepest point beneath the pit highwall to the west. This variability in cave lift resulted in highly non-uniform stress and material flow conditions within the draw column, complicating both draw strategy and cave material flow interpretation. A key geotechnical challenge at ADM was the extremely fine secondary fragmentation of the lamproite ore. The lamproite has been described in feasibility studies as 'extremely friable when dry and taking on a putty consistency when wet'. Based on operational observations at ADM, the caved material behaved as a wet, cohesive, fine-grained mass rather than the coarse blocky material anticipated during project design. The 'sticky', fine, wet material was prone to arching, dead zone formation, and preferential chimney caving along structural discontinuities, as well as causing permeability contrasts within the column, a behaviour directly relevant to the flow patterns interpreted in this study.

4 Instrumentation systems installed

4.1 Overview of the monitoring suite

ADM deployed 4 distinct flow monitoring technologies providing complementary spatial and temporal coverage. In total, 400 Networked Smart Markers, 792 Smart Markers for cave flow monitoring, 38 cave tracker beacons, and 264 Smart Markers dedicated to drawbell flow characterisation were installed (Ooi 2023). This multi-technology approach allowed cross-validation between systems and provided a range of spatial densities and temporal resolutions:

- Cave Tracker System: active electromagnetic beacons installed in 2 dedicated installation holes, tracked by a network of fixed detectors on the extraction level, undercut, and level access pump station drives. Several were also manually deposited on the open pit floor at strategic locations, although initially out of range of the underground detector network (Whiteman et al. 2016).
- Smart Markers: passive battery-powered point markers installed in drawbell blast designs and within the caving column; recovered individually at drawpoints and logged against production records.
- Networked Smart Markers: a collaborative Elexon–Newcrest–Rio Tinto development providing both cave back monitoring (time-domain-reflector function) and flow marker capability via a networked string of markers (Steffen et al. 2016).
- RFID cattle tag trial: a lower-cost passive marker trial deployed via drone drops from the open pit surface and through glory holes, tested as a supplementary dense-array flow marker system (Wilson et al. 2018).

4.2 Cave Tracker System: hardware and installation

The CTS was developed by Elexon Electronics, Brisbane in collaboration with Mining3 and the Newcrest/Rio Tinto consortium. The system operates on the principle of low-frequency electromagnetic ranging: each beacon contains a spinning magnetic dipole that generates a rotating magnetic field, which is detected and ranged by fixed detector units mounted in surrounding excavations. Range measurements from at least detectors during a beacon spin event enable multilateration (a surveillance technique that determines an object's precise position by measuring the differences in arrival times of signals) of the beacon's three-dimensional position (Whiteman et al. 2016). At ADM, 76 mm diameter CTS beacons were installed in 2 purpose-drilled installation holes penetrating the caving column above the extraction level. Hole 1 contained beacons BH1#0 through BH1#8 (highest to lowest in the cave). Hole 2 contained beacons BH2#0 through BH2#13. Detectors (prefixed DTR) were installed at 3 levels: in the extraction drive (ED) ribs, in undercut footwall (UC FW) drift up holes, and in the extraction level (EL) downholes. Each installation environment presented distinct challenges. ED rib installations required 250 mm reamers to accommodate detector diameter; initial installations suffered cable damage from load–haul–dumper (LHD) cleaning operations until cables were recessed in PVC-lined channels and shotcreted in place. UC FW uphole installations required manual handling of heavy detector assemblies. EL downhole installations involved lowering detectors on rope slings into holes that progressively filled with mud, requiring multiple clean-out and re-attempt cycles. In some cases, beacons were inadvertently advanced into subsurface cavities – interpreted at the time as fault/shear gaps where drillers had lost returns, which influenced initial positions and subsequent movement interpretations.

Detector connectivity was managed through a network of ITCAM (cave tracker beacon reader) units connected to the mine network, enabling remote monitoring and data download. Beacon position data was updated approximately every 2–3 days based on spin event frequency, providing sub-weekly temporal resolution over the 2015–2018 monitoring period.

4.3 System range and signal processing

Three categories of range measurement were generated by the CTS for each detector–beacon pair: the partially calibrated beacon range (canonical method), calculated from the semi-minor axis of the received 3D magnetic ellipse, which accounts for beacon rotation but is sensitive to phase noise and local magnetic field distortion; the partially calibrated range estimate (signal magnitude method), generally the most stable indicator but subject to a range offset from beacon orientation; and the filtered range, a manually edited series based on the signal magnitude estimate with interpolation over periods of detector outage, used as input to three-dimensional position calculations.

Several hardware and software improvements were implemented during the trial. A CPU 'quiet mode' software update – placing the detector's processor in a low-emission state during spin events to reduce self-interference with the magnetometer – extended the effective detector range from approximately 120 to 250 m. Revised detector hardware (795 mm in length, compared with earlier versions) further reduced internal noise. Beacon construction was improved through epoxy resin fill and loom rerouting to enhance structural robustness under three-point bending and impact loads during installation and cave transit.

4.4 Smart Markers and RFID trial

The 792 Smart Markers for cave flow and 264 for drawbell characterisation were installed by a combination of drilled string deployments from underground access and drone drops via the open pit surface and established glory holes. Individual markers were assigned installation coordinates based on deployment location and production records. Recovery was achieved by monitoring each ED for marker-detection signals and cross-referencing them with production logs to identify the originating drawpoint.

The RFID cattle tag trial provided a complementary low-cost passive system using recycled agricultural ear tags. While bulk drops were conducted via drone into the open pit, targeted underground deployments by hand into drawpoints, tipples, and onto conveyors were initially performed to test specific segments of the ore handling cycle and the viability of the antenna hardware. Detection was ultimately achieved using a single horizontal panel antenna mounted over the surface conveyor (CV104), following the failure of the vertical antennas in the original three-antenna array design. The system demonstrated detection rates of 44–74% for those tags deployed directly into the underground ore handling system – well above initial expectations of 5–10% – confirming technical viability for dense-array flow tracking applications in future operations (Wilson et al. 2018).

5 Results and interpretation

5.1 Beacon movement: general behaviour

Continuous monitoring of CTS beacons from May 2015 to December 2018 yielded a comprehensive dataset of downward migration through the cave column. The general character of beacon movement was consistent with gravitational draw toward the active extraction footprint, with beacons progressively reducing their range to EL detectors over time. The rate of descent varied considerably between individual beacons, reflecting differences in draw intensity below each beacon's lateral position, the degree of drawcone development, and local cave mass characteristics. By March 2018, Beacon BH2#10 (serial 7JR8) had been reported at the EL drawpoint area, going offline on 6 January 2018 approximately 15 m above the extraction drawpoint. Magnetic field distortion from reinforcement steel in the EL infrastructure degraded the ranging accuracy during the final approach, making it likely that the beacon went offline during the extraction process. Beacon BH2#12 (serial 7JRI) was approximately 21 m from the EL at the time of the final report – a prime candidate for physical recovery for engineering assessment (Elexon Electronics 2018). Beacons installed in the upper UG16 horizon (>240 m from the nearest detector) remained out of range throughout the monitoring period, highlighting the range limitations of the system at the time.

5.2 Isolated drawcone formation: key examples

The most significant operational finding from the CTS data was clear evidence of isolated drawcone behaviour across substantial portions of the ADM footprint. Rather than exhibiting broad, overlapping gravity flow zones consistent with interactive draw, multiple beacons demonstrated tightly constrained vertical migration trajectories, moving predominantly downward with minimal lateral displacement from their installation positions.

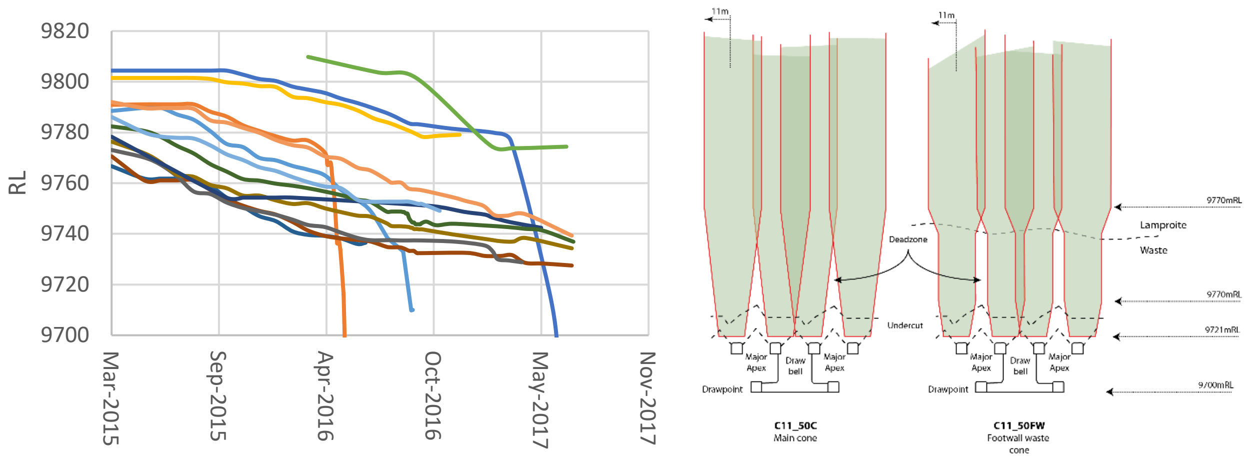


Figure 2 Plot showing multiple beacons demonstrating tightly constrained vertical migration trajectories

This behaviour was corroborated by surface observations. Following the cave breakthrough to the pit floor, chimney-like collapse features (glory holes) formed at specific pit floor locations. Markers dropped into these chimneys were recovered at drawpoints within days to weeks, having travelled near-vertically through hundreds of metres of cave column with negligible lateral deviation. The rapidity of recovery and vertical geometry of the travel paths are diagnostic of narrow, isolated drawcone behaviour rather than the diffuse lateral mixing expected under interactive draw conditions.

Figure 3 Ratholing observed on the surface in the Argyle Diamond Mine open pit – evidence of an isolated draw (Ooi 2023)

The consequences of isolated draw at ADM were severe. Cave column material outside active drawcones remained largely immobile, accumulating in dead zones extending up to 70–100 m above the EL between adjacent drawcones. This material contributed to progressive EL damage as unrelieved stress concentrations developed around isolated loaded zones, ultimately resulting in unrecoverable ore tonnage, accounting for approximately 60% of the planned ore reserve that could not be extracted before mine closure (Stegman et al. 2018).

5.3 Lateral displacement: evidence of rilling mechanisms

While the majority of CTS beacons exhibited broadly vertical trajectories, a subset demonstrated notable lateral displacement relative to their installation positions. This lateral movement, observed primarily in beacons installed at greater heights within the cave column (further from the EL), is interpreted as evidence of rilling, the lateral transport of fragmented material along sub-horizontal flow paths along the top of the inclined muckpile–cave back interface, and within the caved column, driven by structural channelling.

Rilling is a flow mechanism distinct from gravity draw: rather than material descending vertically into a drawcone, material at a higher level in the cave can migrate laterally along the upper surface of the cave muckpile (muckpile–cave back interface) before entering a drawcone lower in the column. At ADM, the lamproite ore and surrounding host rocks also exhibited marked contrasts in intact rock strength and secondary fragmentation size, with lithological boundaries and the Gap Fault Zone providing inclined, preferential flow paths for fines material.

The lateral displacement data from CTS beacons provided, for the first time at an operating block cave, direct empirical evidence of rilling-type movement. Beacons that migrated laterally by significant distances before entering the drawcone indicate that real drawzone geometry is significantly more complex than simple cylindrical or ellipsoidal drawcone models used in scheduling packages such as PC block cave (PCBC). If material can rill laterally into adjacent drawcones, then partially isolated drawpoints may continue to contribute to production via rilling pathways, thereby masking the true degree of isolated behaviour from production data alone.

5.4 Smart Marker recovery and drawzone geometry

Of 792 Smart Markers installed for cave flow monitoring, 113 were recovered at drawpoints, representing a 15% recovery rate. This relatively low recovery reflects battery life limitations (5–7 years, depending on the spinning frequency), changes in mine plan and draw strategy, early drawpoint closures, markers potentially destroyed during the caving process, markers stranded in dead zones that would not be expected to report unless draw conditions changed, and deficiencies in the CT system (Ooi 2023).

Despite the low overall recovery rate, the spatial distribution of recovered markers provided important insights. Key observations included:

- Markers seldom crossed between 2 major apexes, confirming limited lateral interaction across the major apices in the herringbone layout, as depicted in Figure 4.

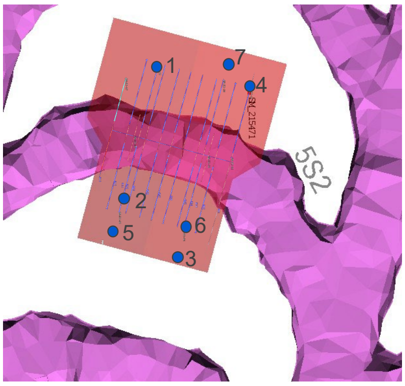


Figure 4 Recovery positions of markers over time (Ooi 2023)

- Estimated drawcone diameters (based on cylindrical drawcone geometry and cumulative recovered tonnage) showed significant variability across the footprint, ranging from approximately 8–22 m, as shown in the plot in Figure 5.

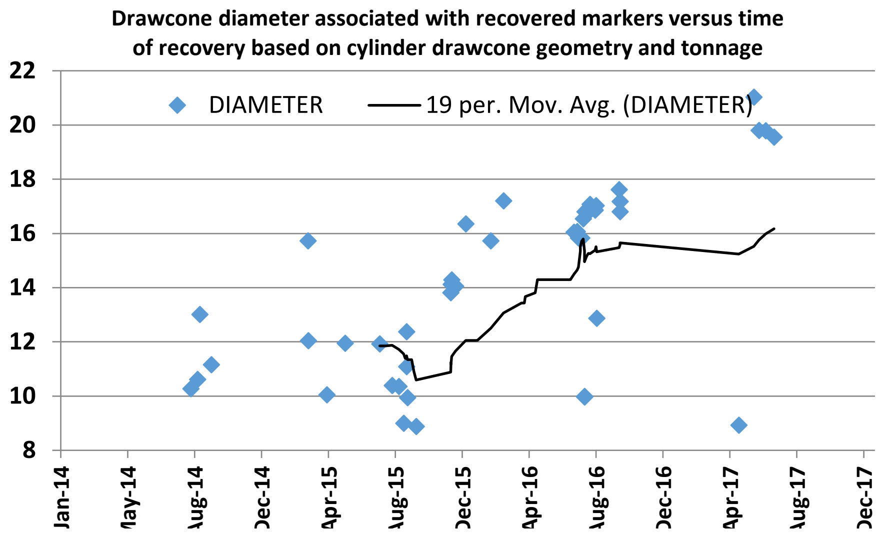


Figure 5 **Drawcone diameters back calculated from marker recovery (Ooi 2023)**

- A significant proportion of marker movement (lateral movement and movement rate) responded to draw strategy changes, particularly following implementation of the load-shedding draw strategy, confirming that draw sequence can be used to actively manage the extent of isolated drawcones.
- CTS beacons provided additional resolution on the vertical distribution of flow behaviour: lateral movement was more frequently observed at greater heights above the EL (consistent with rilling), while beacons closer to the EL showed predominantly vertical descent, consistent with Laubscher's isolated drawcone theory.

Drawbell Smart Markers showed a 35% recovery rate across monitored bells, with recovery timescales ranging from one month to over 36 months after blast (Figure 6) and cumulative EL tonnage at recovery exceeding 25,000 t in several cases. The extended recovery timescales and low proportion of markers recovered from minor apex zones are consistent with the existence of a dead zone at the minor apex where material is not entrained into the drawcone.

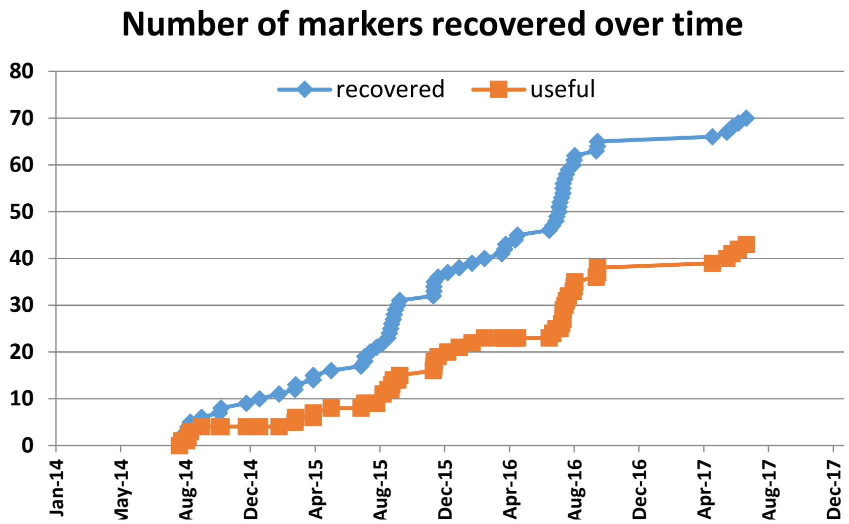


Figure 6 **Number of markers recovered over time (Ooi 2023)**

6 Consequences for cave flow and draw control

6.1 Draw strategy and interactive draw

The ADM instrumentation results collectively confirm that the draw strategy is the primary controllable variable governing whether a block cave achieves interactive or isolated flow. The integrated marker dataset demonstrated clear sensitivity of cave material flow to draw sequence: markers responded to changes in load-shedding draw strategy, and drawcone diameters were responsive to draw intensity at adjacent drawpoints. These observations are consistent with Laubscher's interactive draw theory, which predicts that overlapping gravity flow zones from adjacent drawpoints can mobilise material from between drawcones, provided a sequenced draw is applied at sufficient intensity to the neighbours of any restricted or closed drawpoint.

The practical implication for draw control is that real-time cave flow monitoring enables draw decisions to be made on a data-driven rather than model-predicted basis. At ADM, cave tracker data allowed geotechnical engineers to identify developing isolated zones before they were fully established, providing the earliest possible opportunity to implement compensating draw strategy adjustments – including load-shedding to peripheral drawpoints and selective over-drawing of drawpoints adjacent to isolated cones. While not all isolated draw can be reversed once cave column confinement is established, early intervention was demonstrably more effective than late-stage reactive responses.

6.2 Dilution entry minimisation

Isolated drawcones exhaust their ore column at a predictable rate, after which continuing draw preferentially recovers diluting material rather than ore. At ADM, where the cave column comprised lamproite flanked by dolerite, quartzite, and mudstone, dilution entry was always a significant production concern. CTS beacon trajectories that reached the EL from positions at or near the known ore boundary provided evidence that the system could provide notice of imminent dilution entry at specific drawpoints, which would enable targeted draw suspension before dilution concentration exceeded acceptable limits; however, other challenges related to managing convergence, pillar crushing, and inrush risks were of higher priority at Argyle during this period. This capability did prove particularly valuable for planning the then future operations at Oyu Tolgoi, where the ore column geometry is geologically complex and dilution entry from the cave back or flanks would represent a significant reduction in recovered value. Real-time beacon tracking provides an advanced indicator of drawcone exhaustion not available from progressive production grade data alone, since grade dilution typically lags the physical arrival of non-ore material due to column mixing.

6.3 Implications for Oyu Tolgoi and future cave designs

The ADM trial provided Rio Tinto with a validated operational basis for designing the cave flow monitoring system at Oyu Tolgoi. Several specific lessons emerged:

- System reliability: cable management and detector protection are critical to maintaining network uptime. ADM experience with LHD cable damage and ITCAM failures informed the design of hardened, recessed cable installations and improved detector enclosures for Oyu Tolgoi, and armoured cabling and redundant systems planning at the Freeport-managed GBC/DMLZ block caving operations.
- Detector range: the quiet mode software update and extended-length detector hardware – both developed partly in response to ADM operational experience – substantially extended the effective detector range, allowing fewer installations to achieve equivalent spatial coverage. Furthermore, this limited range knowledge was used in the OT CT design, where sacrificial detectors were installed in holes drilled from the surface.

- Installation methodology: ADM experience with cavity losses, manual uphole installations, and muddy downholes directly informed improved protocols and beacon string designs (fibreglass rod and mounts) for subsequent installations at GBC/DMLZ and Oyu Tolgoi.
- Data interpretation: the observation that beacons at greater heights show more lateral movement while those near the EL show predominantly vertical descent provides a depth-dependent flow behaviour framework for calibrating REBOP and other cave flow simulation tools.
- Complementary technologies: no single system provides complete cave flow information. CTS provides time-resolved 3D trajectories for a limited number of beacons; Smart Markers provide higher spatial density with lower temporal resolution; network smart markers (NSMs) provide cave back geometry; RFID tags offer high-density, low-cost supplementary coverage. A balanced mix of technologies was planned for the Oyu Tolgoi deployment.

More broadly, the ADM experience underscores that for any large-scale block cave operating at depth with complex geomechanical conditions, the cost of deploying cave flow monitoring is small compared to the value at risk from isolated draw-driven ore loss. The estimated loss of approximately 60% of the ADM ore reserve, at least partly attributable to isolated draw and draw strategy constraints, provides a compelling cost-benefit justification for comprehensive monitoring investment in future operations.

7 Conclusion

The cave tracker trial at ADM was a world first: the deployment of an active electromagnetic beacon tracking system at full cave-scale in an operating block cave environment. Despite significant installation and commissioning challenges, including cable damage, detector outages, installation hole cavity losses, and the physical demands of heavy detector installations in extreme underground conditions, the system generated a continuous three-year dataset of beacon position data that yielded important insights into cave flow behaviour.

The principal conclusions from the ADM trial are:

- Cave flow behaviour at ADM was predominantly characterised by isolated draw, with individual drawcones exhibiting limited lateral interaction at the 30 × 15 m offset herringbone drawpoint spacing.
- Dead zones of non-interactive material up to 70–100 m in height developed between drawcones above the EL, confirming that a significant proportion of ore column material is effectively inaccessible under isolated draw conditions.
- A subset of beacons demonstrated significant lateral displacement at height within the cave column, providing direct evidence of rilling-type material movement along the top of the muckpile/cave back interface, as well as structural or lithological interfaces, with important implications for drawcone geometry interpretation and flow simulation calibration.
- Draw strategy, specifically sequenced load-shedding draw sequence, demonstrably influenced cave material flow, confirming the potential for real-time flow monitoring to inform proactive draw management.
- The ADM trial provided an essential operational learning platform for the design of cave flow monitoring systems at Oyu Tolgoi, informing hardware improvements, installation protocols, and the multi-technology monitoring philosophy to be adopted at that operation. These learnings also benefited other cave mine installations throughout the world.

The ADM case study demonstrates the transformative potential of real-time cave flow instrumentation for block cave draw control. The lessons learned from this pioneering trial have directly shaped the design of the next generation of cave monitoring deployments within the Rio Tinto portfolio and represent a significant contribution to the collective knowledge base of the global block caving industry.

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