Caving 2010 — Y. Potvin (ed)

doi:10.36487/ACG_rep/1002_1_Fernandez

Design and implementation of a damage assessment system at Argyle Diamond's block cave project

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Abstract

A fundamental concept of rock mechanics establishes that damage may occur as a result of rock mass disturbance due to excavation. Experience in block and panel caving mines indicates that the mechanism and magnitude of damage changes as the cave progresses through the various mining stages of drives development, undercutting, drawbells opening, ore drawing, etc. Recording observations and ground monitoring information facilitates the understanding of both ground behaviour and rock mass mechanics enabling the implementation of cost-effective preventative measures to reduce damage. At Argyle Diamonds Underground Project (ADUP) a damage classification system was developed based on a semi-quantitative methodology by considering in situ ground conditions, mining induced conditions, ground support and reinforcement performance. The subsequent assessment provided a damage descriptive ranking that can be represented by coloured maps and be integrated and back-analysed with other monitoring results, such as convergence information, enabling a better understanding of ground behaviour and damage mechanisms across the block cave mine.

1 Introduction

Early during undercutting at the ADUP induced loads over-imposed on weak rock areas resulted in significant amounts of damage. This was mainly observed in the undercut drill drives and in several extraction level drives. This issue highlighted a requirement for a system of damage assessment that would be able to provide a number of outputs including the ability to:

- systematically identify, locate and classify damage and vulnerable areas within the mine
- damage quantification as the cave progresses
- allow damage patterns to be developed
- compare damage through time as per mining stage
- identify damage mechanisms
- provide basis for the recommendation of rehabilitation
- provide data for the purpose of ground support and reinforcement performance back analysis
- provide information to optimise undercut and block cave sequences/strategies
- improve the ability to 'predict' areas of damage later in the mine life.

2 Preceding

2.1 Mining method

Argyle achieved its undercutting milestone event on 4 October 2008 when the first 'boxhole' and undercutting rings were fired. By the end of September 2009 the undercut had advanced approximately 9,200 m^2 out of a total footprint of 75,000 m^2.

Argyle is implementing an advanced undercut technique using a W-incline undercut design as shown in Figure 1. In a block cave mine the undercut corresponds to the first stage of caving initiation. The objective of the undercut is to create a continuous zone of broken rock at the base of the block cave orebody and to generate instability above it by allowing gravity and stresses to act in the rock mass, thus sustaining the further stage of cave progress which is cave propagation. Details regarding size of excavations and pillars at the undercut and extraction level are shown in Figure 1.

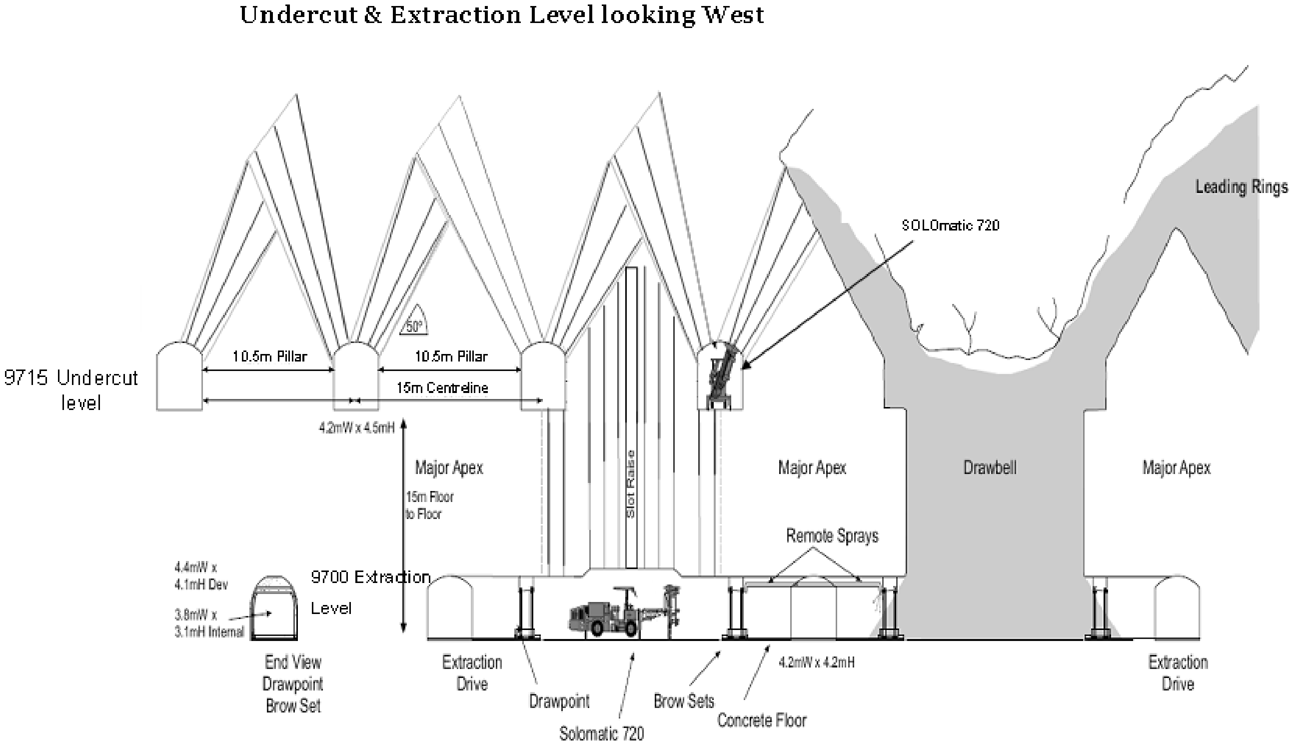


Figure 1 Schematic undercut and extraction level section looking west

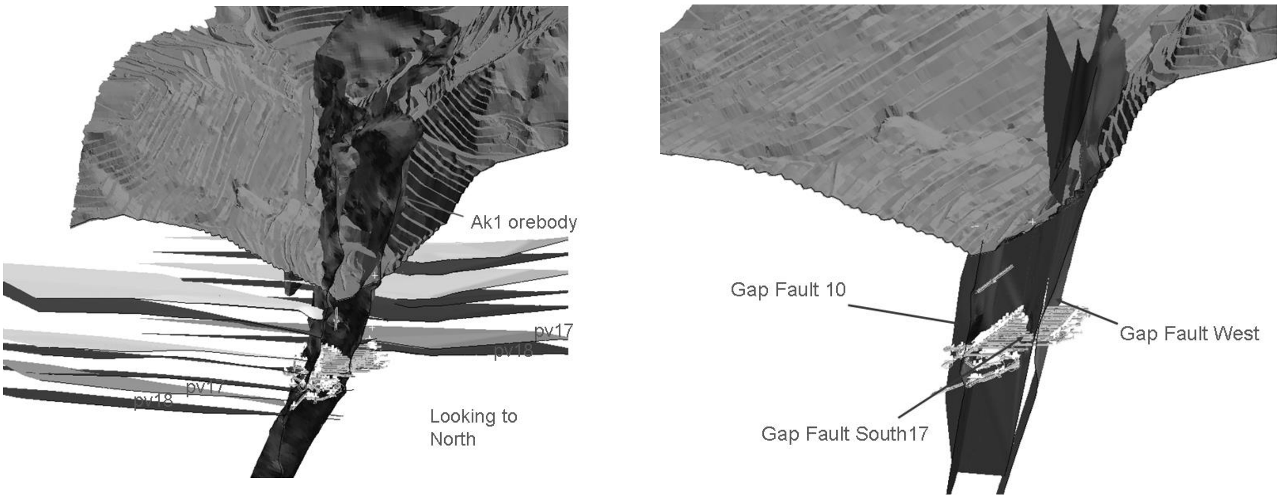
2.2 Geology

2.2.1 Lithology

The AK1 deposit is a volcanic vent intrusion of magmatic lamproite and lamproitic tuff. This was intruded into a Proterozoic sequence of interbedded quartzite, siltstone and mudstone that overlie dolerite and basalt units. Subsequent basement units consist of granite, dolerite, basalt and metamorphosed quartzite and mudstone. Figure 2(a) graphically represents this lithological sequence.

2.2.2 Structures

The Gap Fault system that is made up of a number of fault structures dipping at 60–70° towards 240°, intersects the Argyle deposit and forms the north eastern boundary of the main AK1 pipe on the 9860 m RL horizon. The thickness of the Gap Fault system is between 20–50 m and an apparent vertical downwards displacement of up to 200 m. A geological representation of the main faults and lithological units encountered at the undercut level (9715 m RL) is shown in Figure 2.



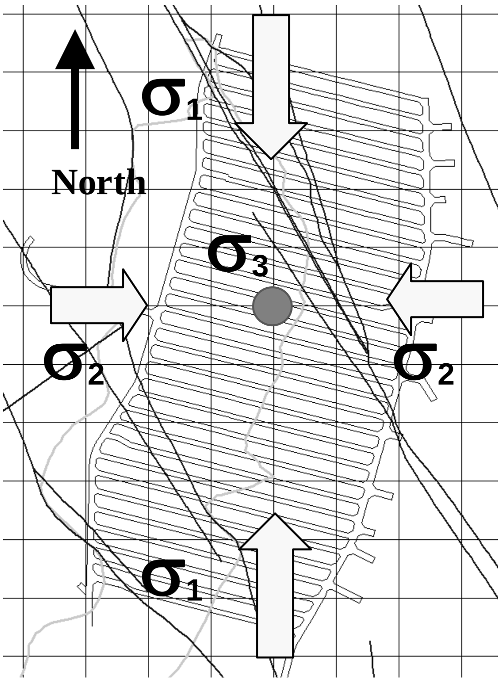
(a) (b)

Figure 2 (a) 3D representation of geological units; (b) 3D representation of major faults (views looking north)

2.3 Geotechnical condition

2.3.1 Stresses

The initial stress field and magnitude of stress ratios based on stress measurements is shown in Figure 3 (Clark, 2009).



Principal Stress	Magnitude (MPa)	Orientation	Dip
σ_1	$= 2.5\ \sigma_V$	North-South	Horizontal
σ_2	$= 1.5\ \sigma_V$	East-West	Horizontal
σ_3	= 0.027 MPa/m	Vertical	Vertical

Figure 3 Pre-mining stress condition at Argyle Diamonds underground mine

2.3.2 Rock properties

The different rock units encountered at the undercut level are represented in Figure 4. Average rock properties are shown in Table 1 (Dight, 2002).

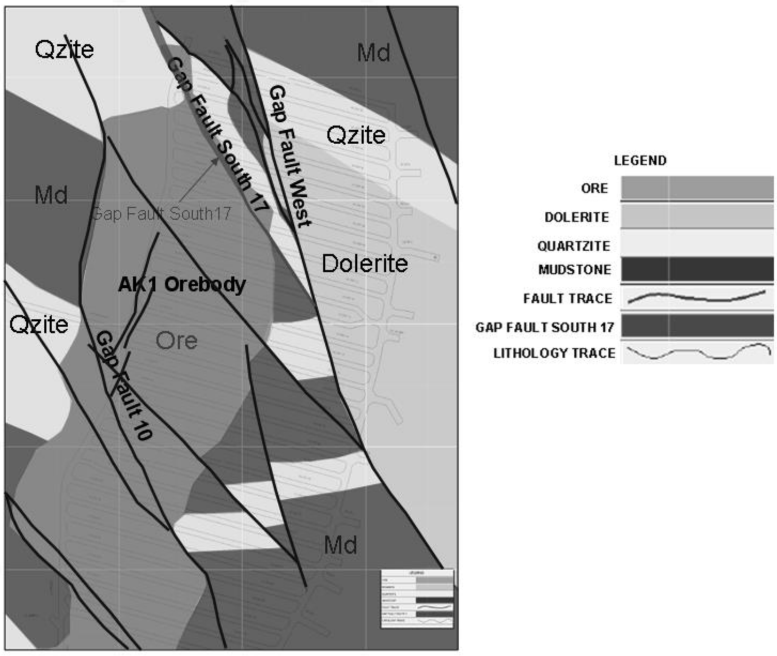


Figure 4 Rock properties at the undercut level

Table 1 Rock properties (average)

Parameter	**Rock Units**			
	Lamproite	**Dolerite**	**Quartzite**	**Mudstone**
UCS (MPa)	85	66	104	35
Young modulus E (GPa)	55	65	52	38
Poisson's ratio υ	0.26	0.36	0.22	0.24
RMR_{1976}	58	55	59	< 45

Stability assessment (Martin et al., 1999) indicates that a failure (damage) mechanism that corresponds to sliding, crushing, squeezing and major convergence (elastic/plastic continuum) would be expected in the weak rock areas that correspond to mudstone and rocks affected by the Gap Fault system. Heavy rockbolt and cable bolt pattern with fibre reinforced shotcrete (fibrecrete) and mesh are recommended by the assessment. In extreme cases, yielding sets may be required. Invert struts or concrete floor slabs may be required to control floor heave. These recommendations are well correlated with current ground support practices at the ADUP.

2.4 Monitored convergence at the block cave area

Horizontal convergence — by using a tape extensometer — has been recorded in a weekly basis from convergence stations installed every 15 m along the undercut and extraction level drives. During the undercutting stage, abutment stress over-imposed resulted in significant convergence in the zones of weak rock mass strength, e.g. in several undercut drives up to 1.2 m wall closure at the position of the brow were recorded. In the areas where significant squeezing was predicted, heavy-yielding supports consisting of resin rockbolts, fibrecrete, straps and de-bonded cable bolting (6 m long cable bolts) were installed. Additionally, a series of undercut guidelines have been implemented for managing convergence. These guidelines comprise: an adequate rate of advance (at least 10 m/month), undercut geometry — concave shape to solid (Brown, 2002), lead-lags ($\leq$12 m in fair ground and $\leq$8 m in poor ground), and undercut front/face oriented perpendicular to the Gap Fault system. The cumulative squeezing of the undercut drives (October 2009) is represented in Figure 5. Convergence rates between 3 and 6 mm/day are regularly recorded, however, up to

17 mm/day has been recorded in the undercut drives. A contour plot showing the results recorded from one week during the month of October is shown in Figure 6.

Note that gray coloured circles shown in Figures 5 and 6 represent the location of convergence stations — which were installed every 15 m along the drives — at the undercut level.

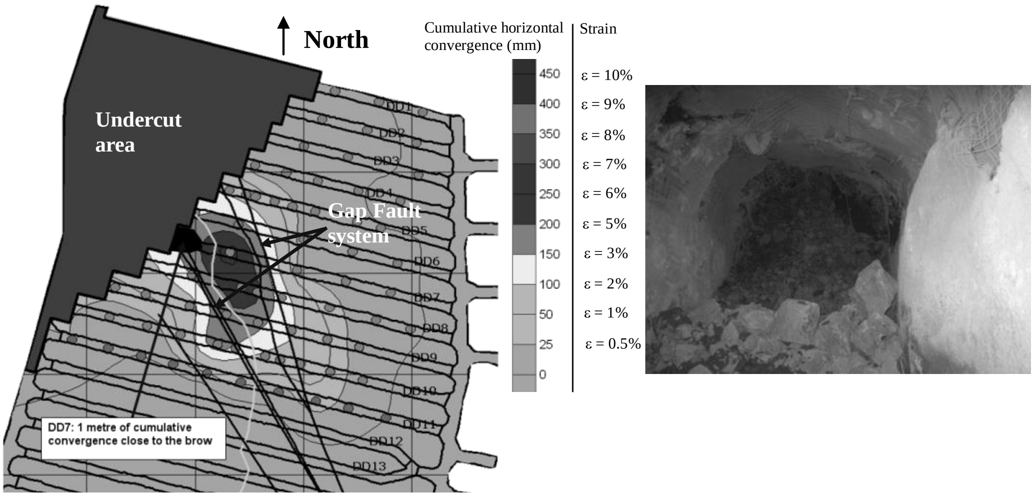


Figure 5 Cumulative convergence at the undercut level (21 October 2009), photo on the right is an example of high squeezing at the undercut brow (Fernandez and Evans, 2009)

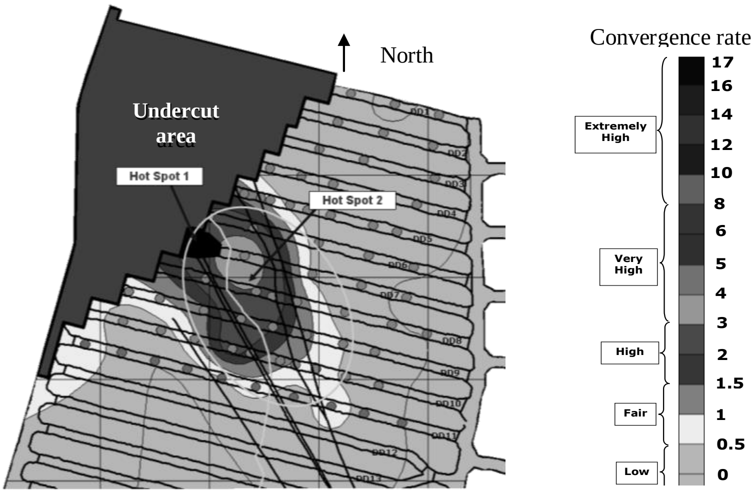


Figure 6 Convergence rate (mm/day) on the undercut level (21 October 2009) (Fernandez and Evans, 2009)

3 Damage assessment methodology

Experience in block and panel caving mines indicates that the damage mechanism and its magnitude change as the cave progresses through the various mining stages (Constanzo et al., 1998). These mining stages would correspond to drives development, undercutting, drawbells opening, and production drawing. Three main factors may affect the stability of excavations: (1) abutment stress induced by the undercut; (2) rock mass relaxation with a subsequent reduction of rock mass confinement (or 'clamping stress' reduction on the geological structures) once the undercut passes over the areas; and (3) damage induced by vibration during undercutting and/or drawbell construction. Other sources of damage could be associated with point load transfer (thus indicating remnant pillars due to poor drill and blast practices); rock relaxation by drawbell construction and/or drawing; seismicity (rock bursts and strain bursts); and stress transferring associated with consolidation of undercut rock.

Any quantitative or semi-quantitative damage classification system must take into account the in situ ground conditions relative to rock mass and stresses; mining induced conditions (e.g. how the stress changes affects the rock mass); and ground support and reinforcement performance.

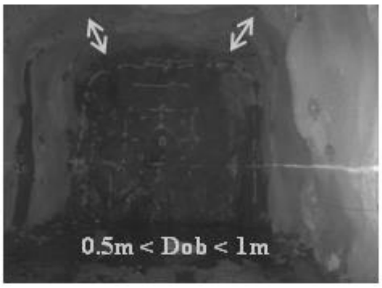
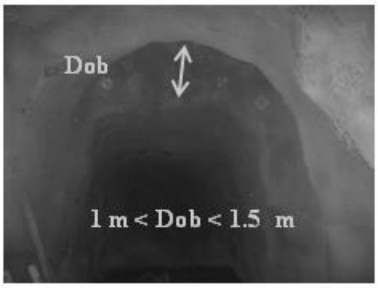
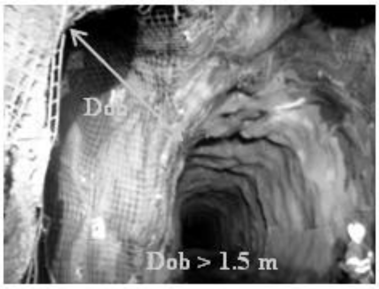
The parameters which are considered in the following semi-quantitative damage assessment corresponds to overbreak, water infiltration and reinforcement/support condition (Fernandez, 2008).

3.1 Description of parameters

3.1.1 Overbreak

Damage by overbreaking of both vertical and horizontal (or inclined) excavations must be considered in any damage assessment. Overbreak could negatively affect the stability of excavations by increasing their size and spans, thus requiring longer anchorage rockbolts and/or cable bolts to maintain a certain designed level of stability. Overbreak must be reduced to maximise the self-supporting capacity of the rock mass. An overbreak classification system for damage assessment is shown in Table 2 (Fernandez, 2008).

Table 2 Overbreak classification

Condition	Description	
Most of half barrels are observed Depth of overbreak Dob < 0.5 m	Observation of half barrels around the excavation indicates very low blast disturbance during development and subsequently very good stability condition of backs and walls. The required length of rock reinforcement (bolts and/or cable bolts) corresponds to the proposed design.	
Depth of overbreak 0.5 < Dob < 1 m	Half barrels not observed. Rock mass around the excavation has been slightly affected by mining. The length of rock anchors (rockbolts and/or cable bolts) is at least 30 cm lower with respect to the original design.	
Depth of overbreak 1 m < Dob < 1.5 m	Rock mass around the excavation has been moderately affected by mining. The observed length of rock anchors (rockbolts and/or cable bolts) is at least 50 cm lower with respect to the original design.	
Depth of overbreak Dob > 1.5 m	Rock mass around the excavation has been highly affected by mining. The observed length of rock anchors (rockbolts and/or cable bolts) is at least 70 cm compared to the original design.	

3.1.2 Water infiltration

Water reduces the strength of a rock mass and its support. Corrosion has been found to be in part responsible for 29% of all rockbolt failures and 25% of all cable bolt failures during rockfalls within the Australian mining industry (Potvin et al., 2001). Sundholm (1997) suggests that corrosion is one of the major factors determining which reinforcement type can be used as permanent support.

Rise and changes in the water infiltration regime in response to the cave progress are expected in block caving mines. An example being, water infiltrations observed in the borders of the cave are typical indicators of rock mass fracturing response to abutment stresses induced by the undercut front. A water infiltration classification system used for damage assessment is shown in Table 3.

Table 3 Water infiltration

Condition	Description
Dry	Excavation surfaces do not indicate any evidence of water infiltration due to rock mass fracturing.
Damp	Excavation surfaces indicate slight and spot evidences of water infiltration due to rock mass fracturing.
Drip	Excavation surfaces show evidence of moderate water influx caused by rock mass fracturing.
Rain	The surface of the rock mass shows high and permanent water influx associated to rock mass fracturing.

3.1.3 Support condition

The term ‘support’ (Brown, 2002) is widely used to describe the procedures and materials used to improve the stability and maintain the load-carrying capability of rock near the boundaries of underground excavations. The primary objective of support practice is to mobilise and conserve the inherent strength of the rock mass so that it becomes self-supporting.

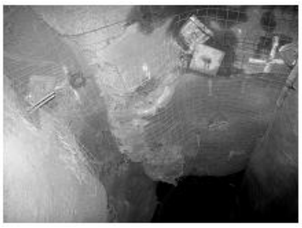
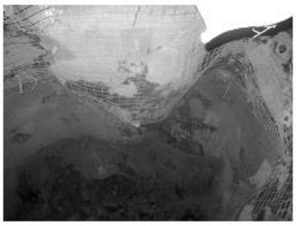
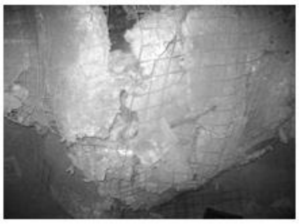
In accordance with modern practice, particularly in Australia, a distinction will be made between the terms support and reinforcement, using the definitions introduced by Windsor and Thompson (1993) and Windsor (1997). Support is the application of reactive force to the surface of an excavation and includes techniques and devices such as timber, fill, shotcrete, mesh, steel or concrete sets and liners. Reinforcement, on the other hand, is a means of conserving or improving the overall rock mass properties from within the rock mass by techniques such as rockbolts, cable bolts and ground anchors.

Damage classification for both reinforcement and support systems are described in Tables 4 and 5 respectively.

Table 4 Damage classification for reinforcement (bolting and cables)

Condition	Description	
Normal	Bolts and cable bolts plates do not show any evidence of loading since its installation.	
Isolated loading	Isolated bolts and cable bolts plates evidence some deformation caused by loading.	
Multiple loading	Multiple deformations of bolts/cable bolt plates and isolated failure of friction stabilisers caused by excessive shear loading (guillotining) are observed.	
Isolated failure	Isolated failure of resin bolts plates (shear failure), evident high deformation caused by excessive loading in cable bolt plates.	
Significant failure	Significant and multiple failure of resin and friction bolts and isolated failure of cable bolts.	

Table 5 Damage classification for support (fibrecrete and mesh)

Condition	Description	
Normal	No cracking and no evidence of loading is observed in mesh and/or fibrecrete.	
Minor cracking	Minor and spot cracking (< 10 mm wide) and minor mesh deformation are observed.	
Multiple cracking and minor slabbing	Multiple cracking (10–20 mm wide), minor slabbing, exposed mesh with isolated broken welds are evidenced.	
Multiple cracking and fibrecrete/strands failure	Multiple cracks > 20 mm wide, multiple fibrecrete slabbing, and multiple breaking strands are observed.	
Significant failure	Failure of fibrecrete and majority of mesh welds/strands are observed.	

3.2 Damage rating

Table 6 gives the classification and scores of individual parameters used to obtain the damage index for excavations. The overall damage classification (rating) is shown in Table 7 (Fernandez, 2008).

Table 6 Damage classification and rating

Parameter	Description	Value
Overbreak	< 0.5 m overbreak	25
	Up to 1 m overbreak	16
	1.0–1.5 m of overbreak	12
	> 1.5 m of overbreak	8
Water infiltration	Dry	15
	Damp	12
	Drip	8
	Flowing/rain	5
Reinforcement condition (bolting and cables)	Normal/no visual evidence of loading.	30
	Isolated plates loaded.	25
	Multiple plates loaded, isolated failure of friction stabilisers.	17
	Isolated failure of resin bolts plates, loading evident in cable bolts plates.	10
	Significant and multiple failure of friction and resin bolts and isolated failure of cable bolts.	5
Support condition (fibrecrete and mesh)	Normal/no cracking and no evidence of loading observed in mesh and/or fibrecrete.	30
	Minor and spot cracking (<10 mm wide) and minor mesh deformation are observed.	25
	Multiple cracking (10–20 mm wide), minor slabbing, exposed mesh with isolated broken welds are evidenced.	17
	Multiple cracks > 20 mm wide, multiple fibrecrete slabbing, and multiple breaking strands are observed.	10
	Failure of fibrecrete and majority of mesh welds/strands are observed.	5

Table 7 Damage classification and overall rating

<table>
<tr><th>Damage Classification</th><th></th><th>Damage Description</th><th>Rating</th></tr>
<tr><td>Minor</td><td>
</td><td>Minor and spot cracking (< 10 mm wide), commencement of fibrecrete slabbing and/or minor mesh deformation. Evidence of spot loading in rockbolts plates, primarily in friction stabilisers. Up to 0.5 m overbreak and wet condition may be observed.</td><td>87–71</td></tr>
<tr><td>Moderate</td><td>
</td><td>Multiple cracking (10–20 mm wide), fibrecrete slabbing, exposed embedded mesh with isolated broken welds are evidenced. Increased load in rockbolts and cable bolts plates. Failure of friction stabilisers and isolated failure of resin bolts plates. Up to 1 m overbreak and dripping condition of water influx could be observed.</td><td>70–50</td></tr>
<tr><td>High</td><td>
</td><td>Multiple cracks (> 20 mm wide), multiple fibrecrete slabbing, failure behind mesh and failure of mesh (broken welds and strands) are evidenced. Significant and multiple failures of friction and resin bolts and isolated failure of cable bolts are observed. Up to 1.5 m of overbreak and dripping to rain water influx could be observed.</td><td>49–33</td></tr>
<tr><td>Collapse</td><td>
</td><td>Massive failure of fibrecrete and mesh strands occurs. High significant cracks and open rock blocks are observed. Significant and multiple failures of rockbolts and cable bolts are observed. Overbreak is usually higher than 1.5 m and high flowing/raining water could be observed.</td><td>< 33</td></tr>
</table>

Note: Overall rating between 88 and 100 reflects that drives have not being damaged.

3.3 Example of application

The damage mapping methodology has been applied in the undercut level during the September–November 2009 period, by considering three different dates of assessment: 26 September, 14 October and 4 November. An example of a data logging sheet is shown in Figure 7.

26/9/09 **Damage Assesment Template**

Level	[illegible]	Drive		Chainange		From:	RS6	To: FW
Rock Type (if known):				Survey Station:				

		Value	Rating
Over Break:	< 0.5m overbreak	25	25
	Up to 1m of overbreak	16	
	1.0m to 1.5m of overbreak	12	
	> 1.5m of overbreak	8	
Water Infiltration:	Dry	15	15
	Wet	12	
	Drip	8	
	Flowing/Rain	5	
Bolting/Cables	Normal/No visual evidence of loading	30	25
	Isolated plates loaded.	25	
	Multiple plates loaded, isolated failure of friction stabilisers.	17	
	Isolated failure of resin bolt plates, loading evident in cable bolts plates.	10	
	Significant failure of bolt plates and isolated failure of cable bolts.	5	
Fibrecrete/Mesh	No cracking/No loading of mesh	30	30
	Minor cracking <10mm (spot cracking)/ Minor mesh deformation	25	
	Cracking 10-20mm, minor slabbing (multiple cracks)/ Broken welds, exposed mesh.	17	
	Multiple cracks >20mm wide/ Strands breaking/cut	10	
	Failure of fibrecrete, majority of mesh welds/strands	5	
		Total	

Rating	**100-88**	**87-71**	**70-50**	**49-33**	**<33**
Description	No Damage	Minor Damage	Moderate Damage	High Damage	Collapse/ Unworkable

Comments: ______________________________

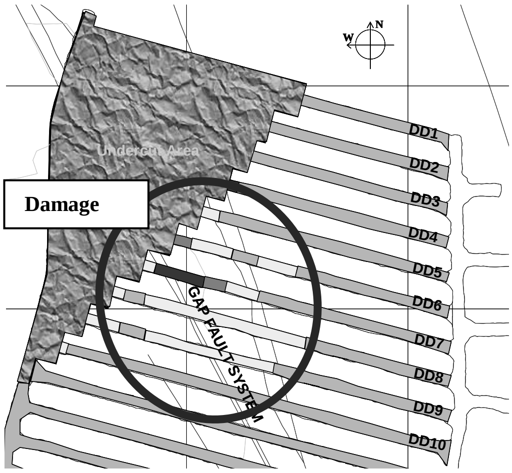
Figure 7 Damage assessment data logging sheet

3.4 Data analysis

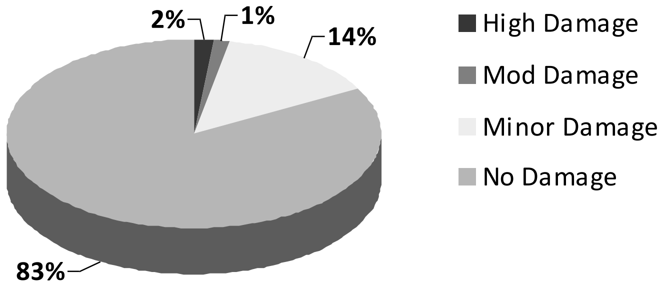
Damage has been represented by colour contours relating to damage classification. Furthermore, the undercut blasted area (location of the undercut front) for each period of evaluation was represented in the damage mapping. A description and comments relating to each period of damage mapping is included in Table 8.

Table 8 Damage mapping description for each period

Damage: September 2009

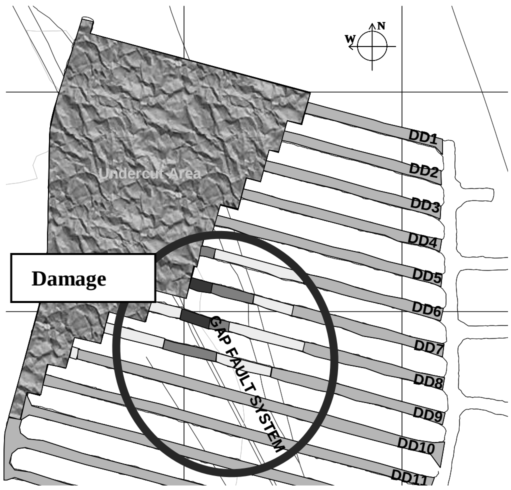


Statistics: September 2009

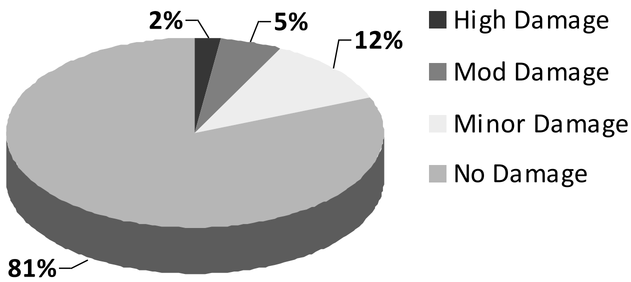


Damage assessment performed during September 2009 indicates that 17% of the evaluated area of the undercut level (UCL) evidences damage. No damage was recorded in the rest of the area (83%). The damage distribution corresponds to: 2% high damage, 1% moderate and 14% minor damage.

Damage: October 2009

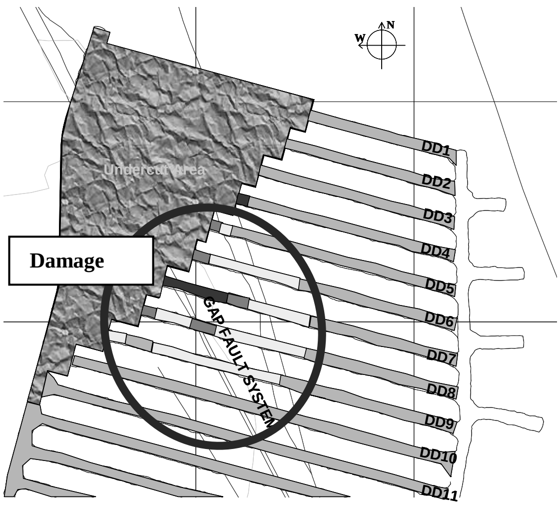


Statistics: October 2009

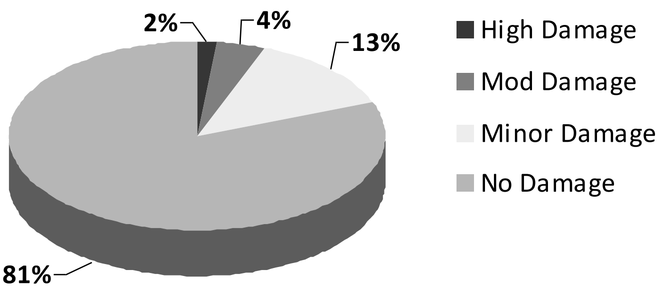


Damage assessment performed during October 2009 indicates that 19% of the evaluated area of the UCL evidences damage. No damage was recorded in the rest of the area (81%). The damage distribution corresponds to: 2% high damage, 4% moderate and 13% minor damage.

Damage: November 2009



Statistics: November 2009



Damage assessment performed during November 2009 indicates that 19% of the evaluated area of the UCL evidences damage. No damage was recorded in the rest of the area (81%). The damage distribution corresponds to: 2% high damage, 5% moderate and 12% minor damage.

Note that moderate damage during November was smaller than in October due to change in ground conditions.

The previous information demonstrates that an 80 to 20% no-damage to damage ratio has been maintained during the evaluated period.

In Figure 8, damage distribution per undercut drive during September 2009 indicates that relevant damage (high and moderate) was concentrated mainly in drives DD6 and DD7 whilst minor damage was encountered at DD8 and DD9.

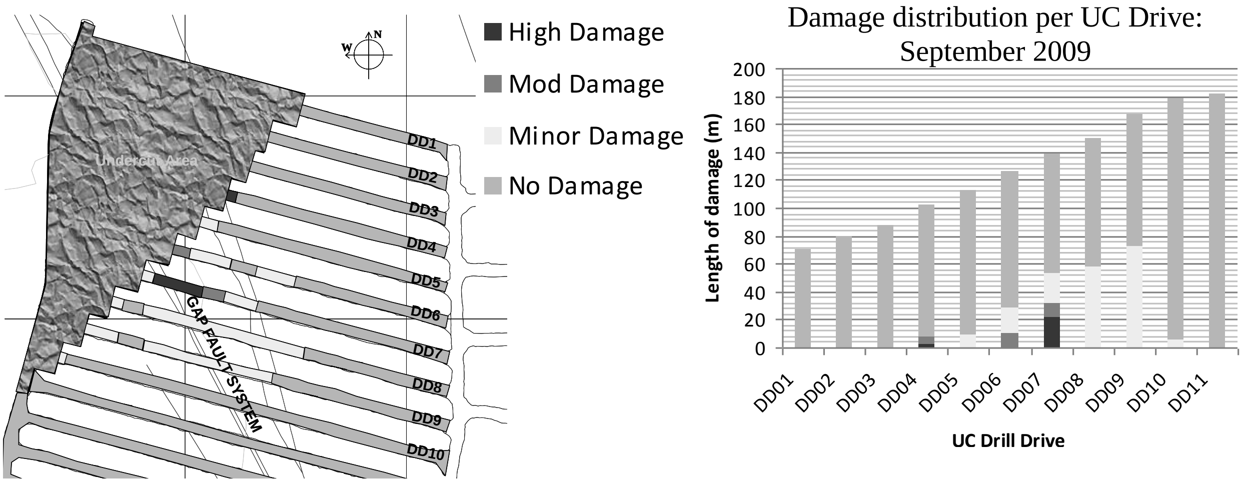


Figure 8 Mapping and damage distribution per undercut drive, September 2009

Convergence monitoring during September indicates that high cumulative convergence, between 200–300 mm of closure (or 5–7% strain) was measured at DD6 and DD7 whilst up to 200 mm of convergence (5% strain) was recorded at DD8 and DD9, this is illustrated in Figure 9 with a contour plot showing cumulative convergence.

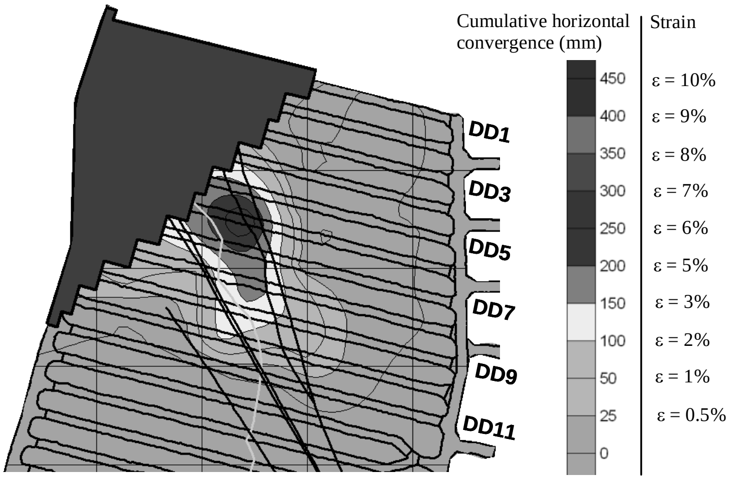


Figure 9 Convergence contouring at the undercut level, September 2009

The previous information indicates that cumulative convergence between 200–300 mm (5–7% strain) can be associated with moderate and high damage at DD6 and DD7 whilst less than 200 mm of convergence (< 5% strain) can be associated with minor damage encountered at DD8 and DD9.

As is shown in Figure 10, damage distribution per undercut drive during October 2009 indicates high and moderate damage at DD7 and moderate damage at DD8, whilst minor damage was recorded at DD9.

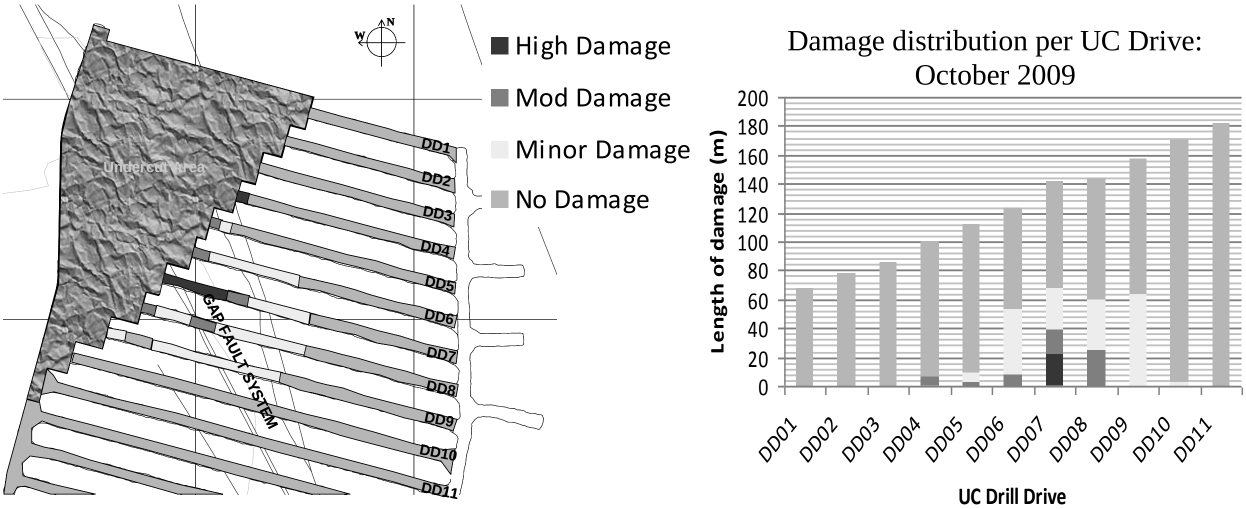


Figure 10 Mapping and damage distribution per undercut drive, October 2009

Convergence monitoring during October indicates very high cumulative convergence, between 300–400 mm of closure (7–9% strain) encountered at DD7 and high convergence (200–300 mm or 5–7% strain) at DD8; whilst convergence up to 200 mm (< 5% strain) was measured at DD9, see Figure 10.

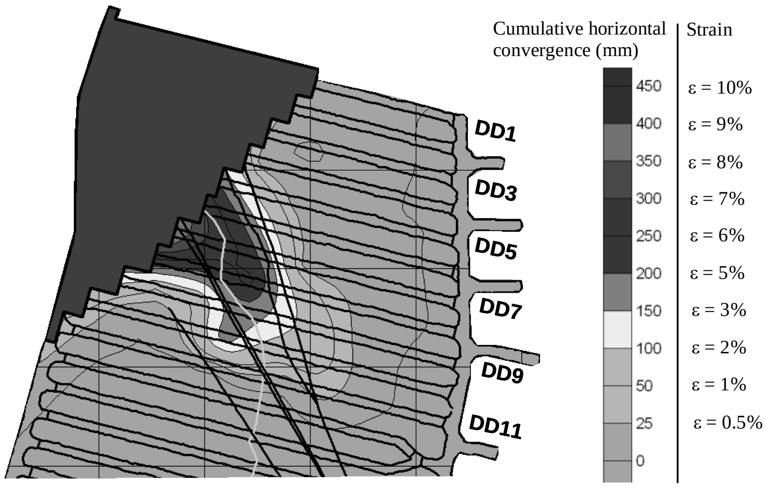


Figure 11 Convergence contouring at the undercut level, October 2009 (Fernandez and Evans, 2009)

The October convergence monitoring information indicates that cumulative convergence between 300–400 mm (7–9% strain) can be associated with high damage at DD7; and cumulative closure between 200–300 mm (5–7% strain) can be associated with moderate damage at DD8; whilst less than 200 mm of convergence (< 5% strain) can be associated to minor damage encountered at DD9.

Similar association regarding the magnitude of damage and the level of convergence was found for the November period. By using the information and analysis described above, it is possible to establish the association between damage and convergence as is shown in Table 9.

Table 9 Damage classification and convergence

Damage Classification	Damage Description	Cumulative Convergence mm	Strain (ε)
Minor	Minor and spot cracking (< 10 mm wide), commencement of fibrecrete slabbing and/or minor mesh deformation. Evidence of spot loading in rockbolts plates, primarily in friction stabilisers. Up to 0.5 m overbreak and wet condition may be observed.	< 200	< 5%
Moderate	Multiple cracking (10–20 mm wide), fibrecrete slabbing, exposed embedded mesh with isolated broken welds are evidenced. Increased load in rockbolts and cable bolts plates. Failure of friction stabilisers and isolated failure of resin bolts plates. Up to 1 m overbreak and dripping condition of water influx could be observed.	200–300	5–7%
High	Multiple cracks (> 20 mm wide), multiple fibrecrete slabbing, failure behind mesh and failure of mesh (broken welds and strands) are evidenced. Significant and multiple failures of friction and resin bolts and isolated failure of cable bolts are observed. Up to 1.5 m of overbreak and dripping to rain water influx could be observed.	> 300	> 7%
Collapse	Massive failure of fibrecrete and mesh strands occurs. High significant cracks and open rock blocks are observed. Significant and multiple failures of rockbolts and cable bolts are observed. Overbreak is usually higher than 1.5 m and high flowing/raining water could be observed.	Collapse condition had not been evidenced. The trigger criterion of rehabilitation considers a cumulative closure of 1,000 mm (or 20% closure). In these cases the walls of the drives are slashed and re-supported to allow the normal operation of undercutting.	

3.5 Damage location

Analysis of the information reflects that at least 75% of the high and moderate damage is located within the Gap Fault area. The distance of damage influenced by the undercut (damage measured perpendicular to the undercut front along the Gap Fault), corresponds to three to four drives (45–60 m). This distance is coincident with the area where more than 200 mm of cumulative convergence (or 5% of strain) has been measured, as is shown in Figures 9 and 11.

4 Conclusions

The proposed and implemented methodology of damage assessment has been developed based on conditions encountered in the ADUP. It has been developed iteratively over a number of months and had been used to comprehensively represent damage conditions as the undercut front advances. Analysis of the information has shown that an 80%/20% no-damage to damage ratio has been maintained during the evaluation period despite the increase in undercut blasted area. Correlation between damage and convergence has been established. Cumulative convergence between 300–400 mm (7–9% strain) was associated with high damage; cumulative closure between 200–300 mm (5–7% strain) was associated with moderate damage; with less than 200 mm of convergence (< 5% strain) resulting in low damage. The zone of moderate and high damage was found to concentrate along the Gap Fault zone perpendicular to the undercut front (which extends up to

60 m). The ground support regime that has been implemented at the ADUP to withstand very severe squeezing (Hoek and Marinos, 2000) has produced the outcome that only in limited areas of extreme squeezing in excess of 1,000 mm (20% strain) has stripping and rehabilitation been required to enable undercutting operations to continue. This issue highlights the importance of the implementation of adequate undercut rates, geometry and shape (lead/lags, concavity to the solid) to maintain drive stability and safety during undercutting.

The longer term implications of correlating damage conditions with convergence and therefore strain are that a practical predictive model can be developed which will be able to forecast the level of damage that is likely to occur in the undercut drives and extraction level drives based on strain modelling; which will allow an optimised level of support and reinforcement to be designed depending on the predicted damage conditions. Such a 'predictive' model will be able to be used in early stage feasibility to estimate the optimal level of support and reinforcing (and to establish a realistic budget and schedule for the work); as well as an ongoing tool for forecasting damage conditions (and remedial support and reinforcing) during undercutting and block caving progression.

Acknowledgements

The writers wish to acknowledge the permission to publish this paper by Rio Tinto and the Argyle Diamonds Underground Project.

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