A Data Science Approach to Identifying and Quantifying Causes of Dilution at Cannington Mine

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ABSTRACT

A data science based dilution study was conducted to identify the causes of dilution at South32’s Cannington Mine (Cannington), a large open stoping operation. In terms of industry benchmarks for unplanned dilution, Cannington is already performing very well, and so opportunities for improvement are more difficult to identify. The study is based upon back analysis of nearly 150 case studies from the mines reconciliation database, and has quantified the relative effect and significance levels for the following dilution parameters; time until paste filling, faulting and cable bolt reinforcement. Specifically, significant contributions were associated with faults and stope open duration. Quantifying the effect of faults on stability graph accuracy enabled a site specific adjustment to improve the predictive ability of the Cannington stability graph (unstable stope specificity improved from 63 per cent to 74 per cent). Despite Cannington’s already high levels of stope performance compared to industry benchmarks, data science methods have identified a complex interaction between identified dilution factors (ie stope open duration, presence of faults and cablebolting). Specifically, a third order Factorial ANOVA (ANalysis Of Variance) provided evidence that stope open duration reduces the effectiveness of cable bolts in faulted ground (average dilution = 2.1 m, p-value = 0.13). These results are consistent with site observations of a relationship between the stope open duration and the extent of failure when unravelling on a fault, even when cables are present.

INTRODUCTION

Estimating and minimising unplanned dilution in open stopes is of critical importance to an operation as it impacts profitability through a number of avenues. Firstly, unplanned dilution in the overall product has negative implications for production and processing efficiencies. The introduction of oversize into the drawpoint can slow down production, and feeding diluted ore into the processing circuit will impact the overall recovery. When overbreak occurs within a stope, depending on the extent of failure, significant risk can be posed to nearby drives and infrastructure. To effectively manage these risks it is crucial to understand what factors influence open stope dilution. Being forewarned of potential stability issues allows for additional measures to be taken (ie monitoring/instrumentation or reinforcement) or re-design of the stopes.

The Mathews stability graph was proposed by Mathews et al. (1980) to predict the stability of large open stopes in deep underground mines. The method suggested that stope stability was primarily a function of stress, stope wall and joint orientations, ground conditions and stope size. Many modifications have been made to the stability graph method over the years with the availability of more data and the use of statistics to better define stability boundaries. The evolution of the stability graph method can be summarised by:

- the original stability graph (Mathews et al, 1980) from back analysis of 50 case histories in North American mines
- re-definition of the stability number (N) through re-calculation of adjustment factors and the re-definition of stability zones by Potvin (1988)
- extension of the database to include more case histories by Potvin (1988) and Stewart and Forsyth (1995)
- use of statistics to better define stability boundaries by Nickson (1992), Hadjigeorgiou, Leclair and Potvin (1995), and Mawdesley, Trueman and Whiten (2001)
- introduction of Mt Charlotte case histories to increase the database to 400 case histories to improve the position of the stability boundaries by Mawdesley, Trueman and Whiten (2001).

The current stability graph method predicts the stability of large open stopes through the use of the modified stability number ($N'$) and hydraulic radius (S) seen in Equations 1 and 2.

$$N' = Q' \times A \times B \times C$$ (1)
where:

\[ Q' \] Bartón’s modified Q-tunneling factor, adjustment factor

\[ A \] accounts for the rock stress factor

\[ B \] accounts for joint orientation

\[ C \] accounts for the design surface orientation as re-defined by Potvin (1988).

\[ S = \frac{\text{Design Area}}{\text{Design Perimeter}} \] (2)

A number of authors have recognised that additional factors have the potential to affect stope wall stability that are not accounted for within the current stability graph method; some of which have been identified by Clark and Pakalnis (1997) as large-scale geological structures, rock reinforcement, drill and blast processes and the time dependency of rock. Fault effects have been investigated by Suorineni, Tannant and Kaiser (1999) through numerical modelling and it was found that fault related overbreak is a function of the non-uniform stress distribution around these structures.

The current study was undertaken with the aim of identifying and quantifying the causes of dilution at Cannington. Cannington is located in central Queensland, approximately 200 km south-east of Mt Isa and is a primary producer of silver, lead and zinc. Localised faulting is present within the orebody with two major structures present in the form of two fault zones; the Hamilton Fault and the Trepell Fault. Conjugate faulting is also present throughout the orebody with two major structures present in the Fault. Conjugate faulting is also present throughout the effects within the database. The test requirements and outcomes are summarised in Table 1. For the purpose of this study, stope case histories have been classified as stable or unstable based on an overbreak cut-off percentage. This can be quantified by overbreak by volume (%OB), as shown in Equation 3.

\[ \% \text{OB} = \frac{\text{Volume of Overbreak on Stope Surface (m}^2\text{)}}{\text{Design Volume of Stope (m}^3\text{)}} \] (3)

Comparisons were also made between equivalent linear overbreak/sloughage (ELOS), see Equation 4.

\[ \text{ELOS} = \frac{\text{Volume of Overbreak on Stope Surface (m}^2\text{)}}{\text{Design Surface Area (m}^2\text{)}} \] (4)

While ELOS is a good measure for looking at geotechnical performance, dilution has been quantified in terms of overbreak by volume. ELOS has also been recognised as being quite variable across stope surfaces within the mine, and it was sought to quantify performance by a measure that could be better used for economic decision-making (ie quantifies dilution). Comparing the difference between using these two measures indicated minimal differences between stable/unstable classifications for stopes within the database. It should be noted that when considering the stability of stope crowns, overbreak by volume can give a misleading stable

### Table 1

<table>
<thead>
<tr>
<th>Statistical test</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-sample T-Test</td>
<td>Test to determine the difference between two population means. Requires two random, independent samples. Requires samples to be normally distributed.</td>
</tr>
<tr>
<td>Mann-Whitney U-Test</td>
<td>Test to determine the median difference between two groups. Non-parametric procedure used for samples that are not normally distributed.</td>
</tr>
<tr>
<td>Power test</td>
<td>Allows the power, sample size or difference in means to be assessed based on a two-sample T-Test. Power value can be used to see if sample error will mislead results and cause the wrong conclusion to be made. A low power value may mean that a mean difference will not be detected, even if one exists.</td>
</tr>
<tr>
<td>Factorial ANOVA (AAnalysys OfVariance)</td>
<td>Used to evaluate interaction between factors. Multiple factors considered simultaneously. Identifies possible sources of bias. p-values for each level of factor interaction.</td>
</tr>
</tbody>
</table>
classification given the effect of scaling. Results related to crown geometries should be carefully considered when using overbreak per cent by volume, and it is recommended that a more suitable overbreak cut-off be developed for the stability classification of stope crowns.

RESULTS

Cannington stope performance

Overview of site performance
Cannington currently uses a site specific stability line (Cannington line) within the updated Mathews stability graph. The Cannington line was developed by Streeton (2000) to capture the site specific nature of stopes at Cannington. Based on a back analysis of twenty stope case histories, the Cannington line was found to be similar to the lower bound of the updated Mathews stability graph proposed by Steward and Forsyth (1995).

By back analysing the performance of stopes within the database, it is clear Cannington is performing well geotechnically. The mean overbreak for all case histories within the database is three per cent. A benchmark of five per cent overbreak was assigned for stable/unstable classification. Any dilution exceeding five per cent was classified as unstable. Out of the 147 case histories within the database 126 could be considered stable and 21 as unstable. The breakdown of the database in terms of stope wall orientations can be seen in Table 2. The majority of case histories come from vertical walls or composite walls (combination of vertical and footwall or vertical and hanging wall).

Effectiveness of the Cannington line

The effectiveness of the Cannington line was assessed by plotting the stable and unstable cases within the Mathews stability graph, see Figure 1. The effectiveness of this line for predicting stope stability can be assessed using two measures:

1. sensitivity – the number of stable cases which correctly report to the stable zone of the graph
2. specificity – the number of unstable cases which correctly report to the unstable zone.

Results of the back analysis indicate the Cannington line is reasonably precise at predicting stable stope behaviour, as the line was able to correctly classify 79 per cent of the stable cases. Issues appear to exist in the stability graphs ability to predict unstable occurrences. The specificity for the Cannington line can only be reported to 57 per cent.

This suggests that other factors may be influencing overbreak that are not accounted for within the modified stability number. These could be due to:
- fault effects
- reinforcement (cable bolting)
- the time dependency of rock (stope stand-up time) (Clark and Pakalnis, 1997).

Causes of misclassification

From the total number of Cannington case histories, ten unstable cases were misclassified within the stable zone of stopes.

<table>
<thead>
<tr>
<th>Hanging wall</th>
<th>Footwall</th>
<th>Crown</th>
<th>Vertical</th>
<th>Composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cases</td>
<td>11</td>
<td>9</td>
<td>14</td>
<td>3</td>
</tr>
<tr>
<td>Median overbreak by volume (%)</td>
<td>3.3</td>
<td>2.6</td>
<td>0.4</td>
<td>1.1</td>
</tr>
<tr>
<td>Median equivalent linear overbreak/sloughage (m)</td>
<td>0.7</td>
<td>0.5</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Total stable</td>
<td>8</td>
<td>9</td>
<td>14</td>
<td>3</td>
</tr>
<tr>
<td>Total unstable</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

FIG 1 – Back analysis of Cannington stopes showing site specific ‘Cannington line’.
the stability graph. Six of these could be attributed to fault related overbreak and one due to the footwall shear zone. The majority of unstable cases can be seen to exist within the R4 mining block. These stopes have been identified as interacting with the Hamilton Fault, which runs through the R4. For the remaining misclassifications two resulted from being subdrilled. A summary of the location and Mathews stability information for these misclassifications can be seen in Table 3.

When considering the effectiveness of the current stability graph method, these subdrill events should be excluded from back analysis. In these cases dilution is driven by operational errors, and not a result of geotechnical influences. By excluding these two cases from the back analysis the specificity of the Cannington line was upgraded to 63 per cent.

### Quantifying fault effects

#### Fault interactions

The results from the initial back analysis indicated that faulting was the major reason behind unpredicted dilution within the Mathews stability graph. To quantify the general effect faulting has on dilution at Cannington, the database was split into ‘fault’ and ‘no fault’ categories. These categories were then analysed using a T-Test and Mann-Whitney U-Test to determine the mean and median overbreak respectively. The results of these statistical tests are shown in Table 4. Given the non-normal distribution of the fault data the median overbreak was used to quantify the overall effect on dilution.

An increased level of overbreak was found to occur when stope surfaces interact with faults. In the majority of these cases the Hamilton Fault or bird faults were modelled to be in proximity of the stope surfaces. A median increase of 4.5 per cent overbreak by volume and an increase of almost one metre ELOS were found for these faulted surfaces. It is clear that under normal conditions, stope performance at Cannington is doing very well. The upper and lower quartiles remain below five per cent overbreak. The dilution associated with faulting is much more erratic and typically generates over five per cent overbreak.

#### Fault adjustment

The effect faulting has on the stability of stope surfaces was significant enough to consider applying an adjustment to the modified stability number. As can be seen in Figure 2, the current Cannington line does not predict the unstable behaviour of stope walls taken in proximity to faults. The stability graph only accounts for 30.8 per cent of unstable cases, leaving the majority misclassified.

The effects of faulting can be quantified by a 3.3–3.6 fold increase in dilution. To adjust the modified stability number to account for this increase, the inverse of these values was taken for both the ELOS and %OB measures for comparison.

### Table 3

<table>
<thead>
<tr>
<th>Mining block</th>
<th>Sequence</th>
<th>Modified stability number (N’)</th>
<th>Hydraulic radius (S)</th>
<th>Overbreak reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>R4 U</td>
<td>Tertiary</td>
<td>5.8</td>
<td>3.6</td>
<td>FW Shear</td>
</tr>
<tr>
<td>R4 L</td>
<td>Tertiary</td>
<td>5.8</td>
<td>5.2</td>
<td>Fault</td>
</tr>
<tr>
<td>R4 L</td>
<td>Tertiary</td>
<td>30.7</td>
<td>6.3</td>
<td>Hamilton Fault</td>
</tr>
<tr>
<td>R4 L</td>
<td>Tertiary</td>
<td>1.1</td>
<td>4.2</td>
<td>Hamilton Fault</td>
</tr>
<tr>
<td>R4 U</td>
<td>Tertiary</td>
<td>66.9</td>
<td>6.3</td>
<td>Hamilton Fault</td>
</tr>
<tr>
<td>R4 L</td>
<td>Tertiary</td>
<td>2</td>
<td>3.5</td>
<td>Hamilton Fault</td>
</tr>
<tr>
<td>QR5</td>
<td>Primary</td>
<td>7.6</td>
<td>7.2</td>
<td>Subdrilled</td>
</tr>
<tr>
<td>P7</td>
<td>Primary</td>
<td>6</td>
<td>6</td>
<td>Hamilton Fault</td>
</tr>
<tr>
<td>ST67</td>
<td>Tertiary</td>
<td>7.5</td>
<td>4.3</td>
<td>Subdrilled</td>
</tr>
<tr>
<td>QR5</td>
<td>Primary</td>
<td>2.4</td>
<td>4.8</td>
<td>Unconfined</td>
</tr>
</tbody>
</table>

### Table 4

<table>
<thead>
<tr>
<th></th>
<th>Mean (T-Test)</th>
<th>Median (U-Test)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cases</td>
<td>%OB</td>
</tr>
<tr>
<td>Fault</td>
<td>20</td>
<td>8.6</td>
</tr>
<tr>
<td>No fault</td>
<td>127</td>
<td>2.1</td>
</tr>
<tr>
<td>p-value</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

ELOS: equivalent linear overbreak/sloughage

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FIG 2 – Fault surfaces plotted within Mathews stability graph showing poor prediction of unstable cases.
For Cannington

$F_{Cannington} = \frac{ELOS}{ELOS_f}$ or $F_{Cannington} = \frac{%OB_f}{%OB}$  \hspace{1cm} (5)

where:

- $F_{Cannington}$ is the site specific fault adjustment factor
- $%OB_f$ is the per cent overbreak attributed to fault interactions

A fault adjustment factor ranging between 0.28 and 0.30 should account for the site specific effects of faulting at Cannington. By re-plotting these cases with the generalised fault factor it was found that a reduction of 0.35 provided the optimum reduction in $N'$, see Figure 3. This adjustment factor improved the specificity (61.5 per cent) of the Cannington line while maintaining the original sensitivity.

Revised stability graph

By applying the fault adjustment factor to stope case histories identified as interacting with faulting, a better prediction of stability can be achieved. Figure 4 shows the improved prediction of the Cannington line with fault interactions accounted for. The modified stability number can now account for the fault effects by applying the site specific fault factor (Equation 6), see Table 5. This adjustment to the modified stability number allows for the site specific fault effects at Cannington to be captured within the Mathews stability graph.

$$N_{Cannington}' = Q' \times A \times B \times C \times F'$$  \hspace{1cm} (6)

The specificity of the Cannington line was improved by 11 per cent after the influence of faulting was accounted for. Table 6 summarises the improved prediction.

Cable bolting effects

Quantifying the influence of cable bolting

The effect of cable bolting on stope wall stability was assessed using the same methodology used for quantifying the effects of faulting. A total of 43 rock surfaces were cable bolted out of the 147 cases. No significant influence on overbreak was detected for cable bolting ($p>0.1$) with results indicating a difference in overbreak of only 0.8 per cent (Table 7).

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**FIG 3** – Fault surfaces re-plotted in Mathews stability graph for adjusted stability numbers.

**FIG 4** – Mathews stability graph re-plotted for adjusted stability number.
A power test was conducted to determine the probability of the T-Test incorrectly detecting no mean difference in overbreak. Power values of 22 per cent and 38 per cent were found for the ‘cabled’ and ‘not cabled’ groups. This indicates there is between a 62–78 per cent probability of incorrectly detecting no mean difference in overbreak in the presence of cable bolting.

Database requirements were determined for increased test power and indicated large sample sizes would be required to detect a small difference in overbreak. To achieve a power value of 80 per cent at a mean difference of 0.8 per cent overbreak, sample size requirements are upwards of 300. This is an unrealistically large number of case histories, considering fault effects could be picked up with sample sizes as small as 20 cases.

A number of inferences can be drawn from these results despite being unable to quantify the effects of cable bolting. These are:

- The database requirement is larger than the number of cable bolted surfaces available for back analysis.
- No significant difference may be a correct inference despite the p-value (p>0.1).
- To fully understand the effectiveness of cable bolting numerical modelling solutions may need to be implemented. Currently comparing ‘apples’ to ‘oranges’ as geotechnical conditions and dimensions are not comparable.
- While no difference in overbreak may be detected in the presence of cable bolting, the dilution which would have occurred if the surface had not been reinforced may have been much higher.

If no major variation in the dilution of cable bolted stopes can be found, this may in fact reflect the effectiveness of cable bolting on restricting overbreak. This is particularly relevant in cases where a cable bolting regime has been implemented to prevent weaker rock types from unravelling into nearby drives.

**TABLE 5**
Fault adjustment factors.

<table>
<thead>
<tr>
<th>Fault interaction</th>
<th>No fault interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cannington fault adjustment factor (F&lt;sub&gt;Cannington&lt;/sub&gt;)</td>
<td>0.35</td>
</tr>
</tbody>
</table>

**TABLE 6**
Summary or sensitivity and specificity before and after fault adjustment.

<table>
<thead>
<tr>
<th>Pre-adjustment</th>
<th>Post-adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>79%</td>
</tr>
<tr>
<td>Specificity</td>
<td>63%</td>
</tr>
<tr>
<td></td>
<td>74%</td>
</tr>
</tbody>
</table>

**TABLE 7**
T-Test results quantifying cable bolt effect on overbreak.

<table>
<thead>
<tr>
<th></th>
<th>Mean %OB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabled</td>
<td>3.6</td>
</tr>
<tr>
<td>Not cabled</td>
<td>2.8</td>
</tr>
<tr>
<td>Difference</td>
<td>0.8</td>
</tr>
<tr>
<td>Pooled standard deviation</td>
<td>4.1</td>
</tr>
<tr>
<td>p-value</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Stand-up time**

Stand-up time is the time taken to backfill the stope after the final mass firing has occurred, and can be used to explore the time dependent behaviour of large open stopes. The time dependent behaviour of rock is well documented, with it being recognised that excavations of certain spans and geotechnical competency have a critical time frame by which they can remain stable if left unsupported. While it would be optimal to backfill stopes immediately after being called empty to eliminate these effects, the availability of resources may restrict the ability of an operation to do so. To assess the effect stand-up time has on overbreak within Cannington stopes, %OB was split into two categories in order to perform a Mann-Whitney U-Test. Results are summarised in Table 8.

An increase in overbreak was evident in stope surfaces that had longer stand-up times. For stopes which were backfilled within three months of the final mass firing, overbreak remained minimal (median overbreak by volume of 1.7 per cent). Stope surfaces that remained standing between three to six months experienced an elevated level of dilution (4.4 per cent overbreak). Figure 5 shows the distribution of overbreak data for stopes which were backfilled within a month, within three months and stopes which were left for between three to six months.

**Interactive dilution factors**

At this stage it is important to note that dilution (ELOS in metres) at Cannington mine isn’t correlated to S (r<sup>2</sup> = 0.002) (Figure 6). This result supports the conclusion that stope design size, S obtained from stability charts has been effective at controlling dilution at Cannington across a wide range of ground conditions, N’. This means that reducing stope size further, is unlikely to result in significant dilution reduction, apart from any potential improvement associated with the fault adjustment proposed in this paper. In light of Cannington’s already high levels of stope performance, achieving further dilution reduction requires more complex analysis (eg Factorial ANOVA (ANalysis Of Variance) to study interaction between dilution factors). Specifically, by analysing interactive dilution factors for stopes with ELOS>1 m, it has been possible to identify dilution factors outside of the stability graph parameters.

Figure 7 provides evidence of interaction between ‘stope open duration’ and the effectiveness of cables in managing fault related instability (p = 0.13). In other words, cable bolt effectiveness is limited by stope open duration, in the case of fault related instability. The vertical bars on the graphs show the 95 per cent confidence intervals for the mean ELOS for each group. It is important to note that the Factorial ANOVA shown in Figure 8 wasn’t biased due to the ground condition factors, N’ and Q’ (Figure 8). Additionally, the effect of total paste dilution and minimum principal stress (σ3) were also analysed as possible sources of bias, but neither of these factors was found to account for the results shown in Figure 7. Whilst a p-value of 0.13 isn’t considered scientifically proven for academic purposes (typically requiring p<0.05), these results are consistent with site observations of a relationship
between stope open duration, and the extent of failure when unravelling on a fault, even when cables are present.

CONCLUSIONS
It can be concluded that a number of external factors are driving unpredicted dilution at Cannington. The most significant of these identified as faulting, primarily through the major structural feature of the Hamilton Fault. The current modified stability number (N') used for the Mathews stability graph does not account for these effects. By applying an adjustment factor based on the median difference in overbreak experienced across the mine, a site specific fault adjustment factor was found to account for fault driven dilution. Stope open duration was also found to influence dilution within open stopes at Cannington. For stopes with stand-up times longer than three months, increased levels of dilution were found. In addition to these findings, third order effects were found to exist between stope open duration, faulting and cable bolting. Factorial ANOVA results paired with site observations indicate cable bolt effectiveness in faulted ground is limited to the duration the stope is left open.

Despite Cannington’s already high levels of stope performance, the application of data science method principles has enabled identification of causes of dilution outside of the standard design methods. Specifically, by analysing the cause of dilution for stopes with ELOS>1 m, it has been possible to identify dilution factors outside of the stability graph parameters.

ACKNOWLEDGEMENTS
We wish to acknowledge and thank South32 for the permission to publish this study and for access to the Cannington stope reconciliation database. We would also like to thank the geotechnical staff at Cannington for their assistance throughout this research project. Their insight and observations of site
FIG 7 – Third order Factorial ANOVA (ANalysis Of Variance) shows the effectiveness of cables when faults are present, and not present; both for conditions when stopes remain open for >28 days, and less than <28 days (third order Factorial ANOVA p-value = 0.13).

FIG 8 – Factorial ANOVA (ANalysis Of Variance) shows no evidence that the results shown in FIG 8 are due to N’ nor Q’ bias.
behaviour greatly assisted in understanding the results seen in the analysis.

REFERENCES


