VII Brasilian Symposium on Rock Mechanics – SBMR 2016
Rock Mechanics and Rock Engineering for Innovation and Development
ISRM Specialized Conference 19-22 October, Belo Horizonte, Minas Gerais, Brasil

Empirical geotechnical improvements for low-angle narrow vein gold mining through modified long hole methodology — experiences from Pilar de Goiás, Brasil

Jaime Andres Corredor Herrera
Pilar de Goiás desenvolvimento Mineral, Pilar de Goiás, Brasil, Jaime.herrera@yamana.com.

Jairo Henrique da Silva
Pilar de Goiás desenvolvimento Mineral, Pilar de Goiás, Brasil, jairo.silva@yamana.com.

Paula Pertile
Pilar de Goiás desenvolvimento Mineral, Pilar de Goiás, Brasil, Paula.pertile@yamana.com.

Gabriel Cezar Portilla Santana
Pilar de Goiás desenvolvimento Mineral, Pilar de Goiás, Brasil, Gabriel.santana@yamana.com

Natalya Raquel Medeiros
Pilar de Goiás desenvolvimento Mineral, Pilar de Goiás, Brasil, Natalya.leitao@yamana.com.

SUMMARY: Narrow vein deposits are highly sensitive to dilution events during extraction stages. This is due to several geological features such as lithology, structural setting, ore thickness or inclination of ore body, therefore conditioning the effectiveness of its extraction methods.
This work reviews the results of continual improvements in extraction methods in a foliated low-angle narrow vein ore deposit in the Brazilian Pilar de Goiás gold mine, through low-angle open stope design.
Since long hole mining was proposed, the establishment of stable span dimensions became a critical aspect for validation and operability of the extraction method. The proposal was initially tested in several panels with ore body inclinations dip varying from 18 to 30°. Detailed underground geological structural modeling allowed the geotechnical department to estimate stable hydraulic radii (HR) obtained empirically using Mathews stability graphs.
As a complement to this approach, several drill and blasting procedures were proposed to improve the final hanging wall. This included 3-2 to 2-1 staggered drilling patterns as a function of ore body width. The aim was to reduce blast damage as much as possible in order to obtain maximum recovery rates of selective high-grade ore production with minimum dilution.
Preliminary results showed three main controlling factors to take into account for successful implementation of a modified low-angle narrow vein long hole stopping method: (1) panels must be projected for inclinations above 25º to optimize fragmented ore removal from the open stope using water jets; (2) increasing the panel length and maintaining its stability when the hanging wall presents the strongest rock type; and (3) correct rib pillar positioning related to the main structural features during preparation stages require strict controls to avoid future unstable roof stope complications as production blasting is being executed.

KEYWORDS: Narrow Vein, Sublevel stopping, Low Angle, Greenstone belt, Schist, Pilar de Goiás

1 INTRODUCTION

The Brazilian Pilar de Goiás mine site is located in the central region of Goiás State, where regional tectonic models locate the mobile belt and thrust belt as the principal geological feature representing an extensive metamorphic greenstone belt as part of Neoproterozoic Orogeny.

The Pilar belt is an extensive foliated metamorphic sequence of alternated meta sedimentary and meta-volcanic units, which serves as the host-rock for three individual gold-bearing laminated quartz regional fault-fill veins, representing the most important targets for the exploration and production of the mine sites.

The main ore deposits High Grade 1 (HG 1), High Grade 2 (HG 2) and High Grade 3 (HG 3) lenses, which correspond to a structurally controlled quartz vein complex distributed along 6 km southwest strike lens with a low to moderate dip (18 to 30°). This dip, according to Dubé and Gosselin (2007), is "hosted by compressional brittle-ductile shear zones and faults with locally associated shallow-dipping extensional veins".

Since 2013, all efforts were focused on reviewing several proposals and modifications to the room and pillar method layouts, having a general assumption that the ore vein has a consistent homogeneous and continuous inclination. In practice, however, the results were not as effective as expected when the orebody showed fold-related gradual changes in dip.

In recent years, an extensive underground structural mapping campaign was conducted to characterise sectors of the mine based on the identification of deformational features, at the metric scale, such as folds, fault and shear zones, in order to determine more accurately the changes in the orientation of the orebody.

With a refined structural model available, it was possible to determine that 18.5% of total resource had zones with steeper inclinations allowing the trialling of low-angle long hole open stoping, using design criteria from the empirical stability graphs methods by Stewart (2005).

These results and conclusions will be analysed in this work.

2 METHODOLOGY

The methodology and design work flow charts in Swart and Handley (2005) were used in the analysis, starting from rock mass characterisation procedures, estimation of potential failure modes and finally following the suggested evaluation and monitoring cycles.

As complementary information, Equivalent Linear Over break or Slough (ELOS) graphical verification for estimation of dilution and its economic impacts were constructed and contrasted with the empirical-based expected result.

3 DATA

3.1 Lithology

Two lithological units were considered in this study.

The graphite schist (GS) unit is the host rock for the main mineralised vein, defined by intense parallel thin quartz vein arrangement, strongly foliated it presents the most favourable geotechnical properties in terms of mechanical strength.

The quartz-sericite schist (QSST) is a relatively less resistant unit than the GS unit related to its high clay content and random interlayered talc rich horizons, sulphide-rich quartz in very thin discordant veins and typically has ductile deformational features such as intense micro folding and crenulations.

3.2 Structural geology

Three main structural features were recorded in a database of 1477 field data, analysed and differentiated in terms of their persistence, spacing and origin for further geotechnical definitions:

3.2.1 Foliation

Main Pole concentration ($S_{\mathbf{n}}$ 21/207).

Foliation is a plane-parallel structure strongly penetrative and responsible for multiple weakness planes (Mandl 2005); consequently, it is the most relevant feature for anisotropy of the rock mass. This work uses the strike variations of this geological feature to delimitate regional folding.

3.2.2 Faults

Discontinuity planes exposing relative displacement between blocks with persistence up to 20 m, show evidence of strike slip kinematic indicators on its surface for determining the sense of shear (Doblas 1998).

J1-59/032: northwest/southeast strike slip movement along lengths up to 750 m was identified for this family. Spacing varies from 15 to 50 m and the predominant fill minerals are quartz, pyrite and some carbonate which exhibit undulating to smooth surfaces.

J2-097/85: NNE transverse fault pattern is restricted to the central parts of the mine recognising a regional systematic parallel repetition every 300 m towards the southwest. These structures were identified as the most important factor in delimitating and interpretation for structural domains.

3.2.3 Joints

J3-82/334: most persistent joint system trends N-S and is characterised by its relatively low spacing locally reaching a minimum of 20 cm. With smooth roughness and pyrite as predominant fill.

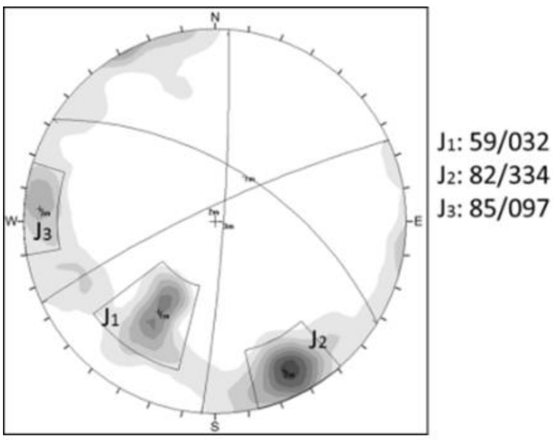

Figure 1 Stereographic representation for the major structural features

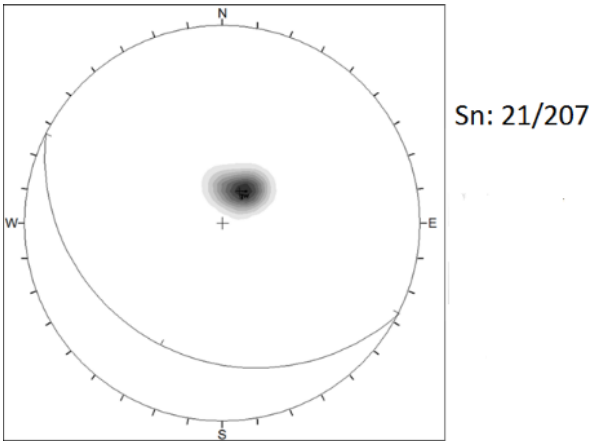

Figure 2 Stereographic representations for foliation.

Table 1. Synthetised geotechnical parameters for each major structural feature.

Joint set	Type	Trend	Persistence (m)	Spacing (m)
Sn	Foliation	21/207	>1000	0,1-0,5
J1	Strike slip Fault	59/032	200	10-50
J2	Normal Fault	82/102	200	1-10
J3	Joint	85/334	0,1-1,0	0,1-5

3.3 Geotechnical parameters

3.3.1 Intact rock strength

A mechanical unit was defined as an individual bed or a package of beds with common mechanical characteristics, including gross lithological character, average bed thickness, presence of slip horizons, and overall macroscopic and microscopic deformation style (Hayes et al. 2008). Therefore, this work will focus on the brittle rheological features of graphite schist to define and quantify the required geotechnical parameters.

The ultimate strength for intact rocks obtained by laboratory test campaign on a total of 48 samples for unconfined compressive strength (UCS) and indirect tensile strength (Brazilian test) considered in this work are in Table 2.

Table 2 Summary of the average intact rock strength results

Lithology	UCS (MPa)	Elasticity (GPa)	Tensile strength (MPa)
Graphite schist	129.9	15.1	13.12
Sericite schist	74.65	54.73	8.35

3.3.2 Rock quality design

In recent published research, the rock quality designation (RQD) is questioned as a methodology (Grenon & Hadjigeorgiou 2003) given the orientation-dependent parameter. This is even more evident when it is applied in highly anisotropic rock material as is the case in the current structural setting. An interesting and very relevant alternative for fracture intensity quantification is offered by Palmstrom (2005), who suggests a three-dimensional volumetric joint index considering the relative spacing values of each family as measurement criteria in Equations 1 and 2.

$$JV = 1/S1 + 1/S2 + 1/S3 + \ldots 1/Sn + Nr/5\sqrt{A} \quad (1)$$

$$RQD = 110 - 2.5Jv \quad (2)$$

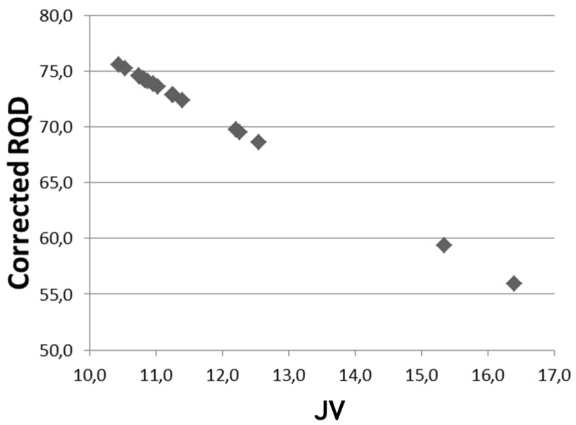

Figure 3 Graphical relationships for Jv and its significance for RQD estimations in anisotropic tabular rock masses.

3.3.3 Rock mass classification

The rock mass rating (Bieniawski 1973) methodology was used for this work considering three relevant features of the rock mass as:

-The contrasting strength between the quartz rich graphite schist host rock and sericite schist lenses present alternately in footwall as well as hanging wall.

-The particular spacing values found for each structural fault system or joint set.

-The relevance of orientation of excavations related to structural features.

Table 3 Rock mass rating and Q values obtained from 35 geotechnical mapping points and differentiated by lithological units

Lithology	RMR	Q
Graphite schist	65-75	11-13
Sericite schist	50-60	5-8

3.3.4 Stope geometry

The initial layout has two parallel galleries developed horizontally and separated by 15 m. Due to the intense foliation of the rock mass, the proposed geometry uses a shanty back having the width of the gallery and ore dip as a condition factor for section and final volume per blast round. The dimensions and geometries are shown in Figures 4 and 5.

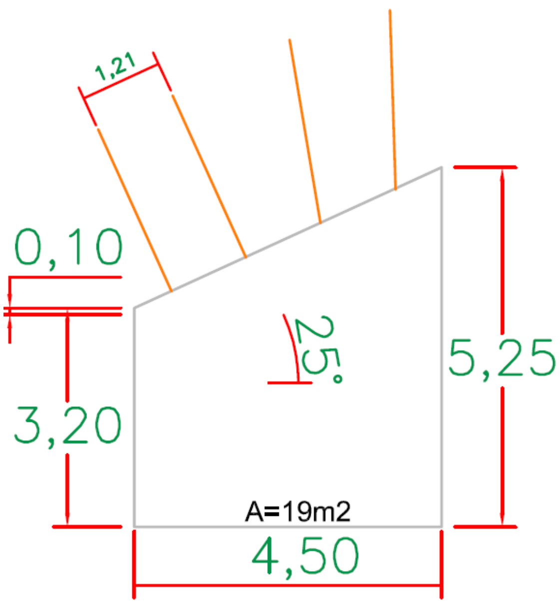

Figure 4 Typical Long hole development section proposed for this work

A second design input is the distance between pillars to determine the most stable span and in this way allows calibrating our empirical analysis; the proposal suggests 12 to 18 m long stopes to maintain hydraulic radii values next to 5.

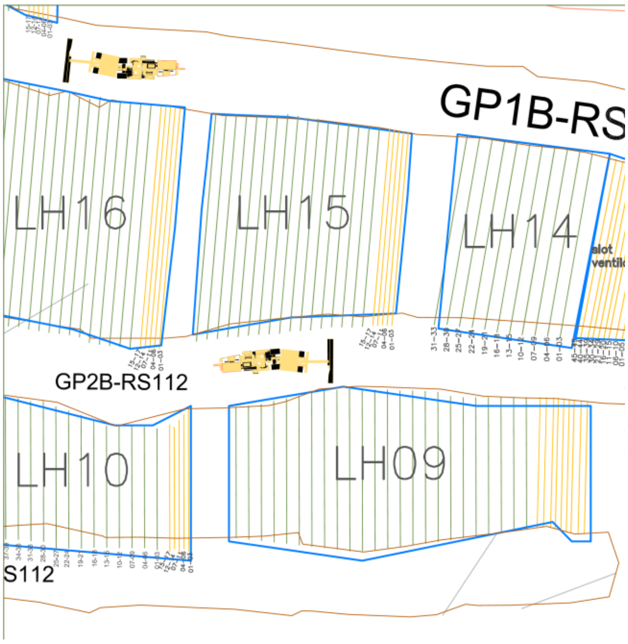

Figure 5 Proposed long hole layout, for scale fan drill length 11 m

4 DRILL AND BLAST PATTERNS AND CONTROLS

Several drill and blast patterns were executed during the trial mining to establish operational parameters. The trials, briefly described in Figure 7, were focussed on cost optimisation via drill metres reduction and powder factor.

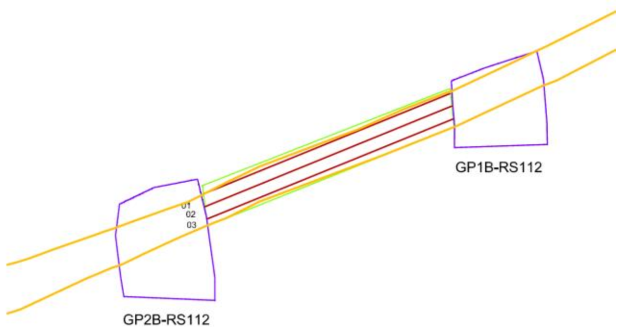

Figure 6 Sections for long hole stopes, highlighting the orebody as irregular lines crossing through excavations, drill pattern expressed by shorter parallel lines (numbered as 01, 02, 03) limited by excavations; inclined distance between galleries is 15 metres.

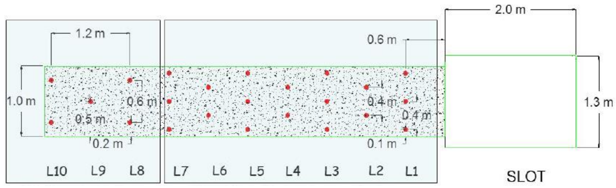

Figure 7 Alternative blast hole pattern array proposed to evaluate specific drill values for 3-2 staggered with 45 mm diameter and 2-1 staggered with 51 mm

5 RESULTS

5.1 Empirical stability graph

For estimation of the maximum stable span for stope design and proposed extraction methods, the empirical Potvin stability graphical was performed and constructed with the onsite geotechnical parameters and considered the observations made by Meló et al. (2014), who attempted to validate the use of the empirical methods in the Brazilian Geotechnical context.

This brief analysis shows that a hydraulic radius of seven is the maximum supported span to ensure the stable condition with the GS hanging wall, with a cable bolted supported stope. The analysis also suggests that there is potential to increase stope size.

Table 4 N' stability number calculated for 15 test panels based on three parameters: stress factor (A), joint orientation (B) and stope geometry (C) and the number of joint sets (Sn, J1 and J2) present in stope analysis

Panel	Joint set	Q	A	B	C	N'
1	Sn	13	1	0.2	3.0	1.7
2	Sn	13	1	0.2	3.0	1.7
3	Sn	13	1	0.2	3.0	1.7
4	Sn	13	1	0.2	3.0	1.7
5	Sn	13	1	0.2	3.0	1.7
6	Sn	13	1	0.2	3.0	1.7
7	Sn + J1	12	1	0.9	3.0	6.9

8	Sn + J1	12	1	0.9	3.0	7.3
9	Sn + J1	12	1	0.9	3.0	7.3
10	Sn	12	1	0.2	3.0	1.6
11	Sn + J1	12	1	0.9	3.0	7.3
12	Sn+J1+J2	8.5	1	0.8	3.0	4.8
13	Sn+J1+J2	8	1	0.8	3.0	4.5
14	Sn	8	1	0.2	3.0	1
15	Sn+J1+J2	8	1	0.9	3.0	4.4

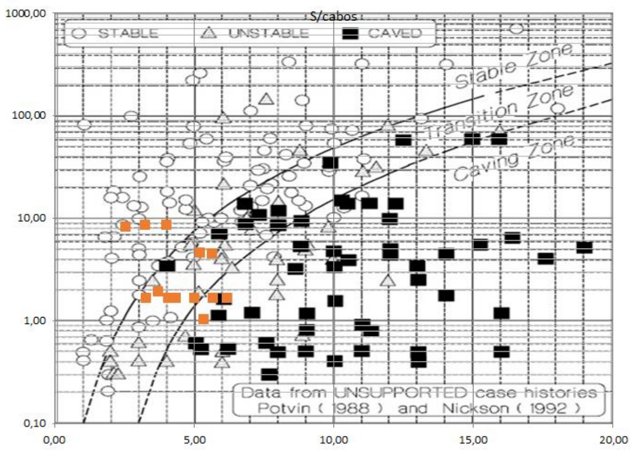

Figure 8 Stability graph for onsite long hole results considering non supported panels

5.2 Dilution estimation

The average thickness of the ore body is 1.5 m, and equipment dimensions are around 3.2 m height, so it is necessary to maintain a balance between dilution and advance ratio.

In the high grade sectors, high dilution with a normal advance rate (3 m advance each two shifts) is adopted to maintain production rhythm.

In the sectors with relatively low grades, the adoption of selective split blasting cycles ensures extraction within cutoff grades but reduces the average development rate (3 m advance each four shifts) with consequent long-term production impacts.

For these reasons the planned dilution is one of the most important factors to be controlled in order to maintain the operability of room and pillar layout.

The ultimate criteria to support the use of the modified low-angle long hole method were the maximum selectiveness, using all the geotechnical and operational procedures discussed above, and avoiding the waste rock removal from the typical operational cycle from room and pillar panels.

Available information from the CMS for 14 stopes was interpreted based on suggested procedures to calculate equivalent linear over break slough (Stewart 2005) using Equation 3.

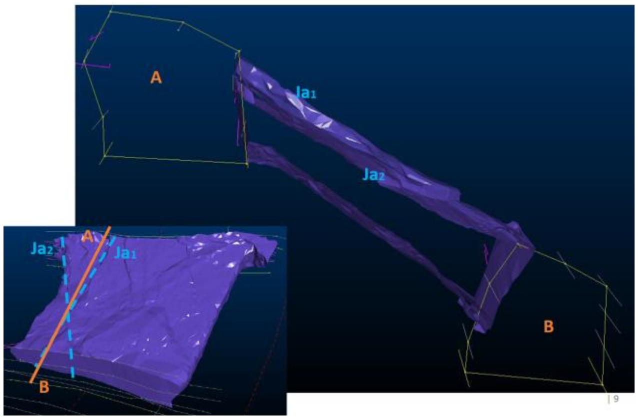

Figure 9 A-B sections from onsite CMS results, showing a successful stope opening. The main structures are indicated by dotted lines

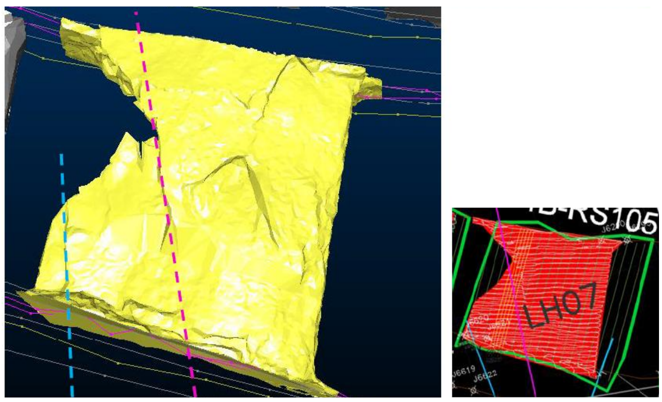

Figure 10 Onsite CMS results for a failed stope opening showing mass lost, roof collapse related to structural controls located near a main structure (dotted lines)

$$ELOS = \frac{Volume\ of\ slough\ or\ overbreak}{(Stope\ height * wall\ strike\ length)} \quad (3)$$

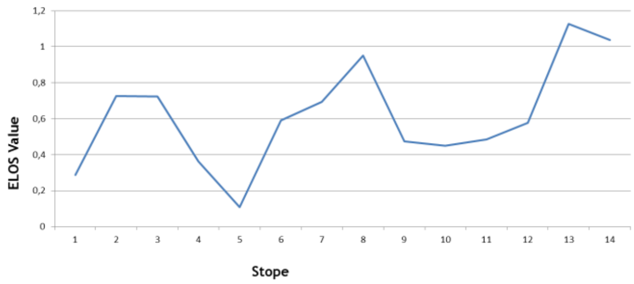

Figure 11 Onsite ELOS calculation results for 14 trial mining stopes

6 CONCLUSIONS

The most important advances in the optimisation procedures for the low-angle narrow vein long hole open stope are:

An exhaustive mapping and detailed structural model was defined to delimitate fold related gentle changes in dip and strike in order to predict ore body behaviour and fault related instability potential for development and production phases.

RQD determinations for foliated rocks through borehole information have to be compared with underground datasets due to the anisotropic nature of the rock mass and important variations related to bore hole orientation.

In Pilar de Goiás, the empirical stability graphs are a reliable tool for stable stope design and can be extended for low-angle inclination cases.

In Pilar de Goiás case study, staggered 2-1 arrangements with 51 mm bits show the most effective blast hole array for ore lenses with less than 1 m thickness; the blast hole arrangement should be modified to test squared blasting arrangements for thicknesses up to 1.5 m.

CMS results from 14 of the executed long hole stopes highlight the importance of structural controls on roof panel stability deduced by the linear features identified on the panels that show higher over break volumes.

Based on the available information, the hydraulic radii showed no important slough/collapse events where no major structural features were present; therefore, it is possible to suggest panel size increase for future extraction panels.

Based on the resultant ELOS values, the methodology becomes efficient for extraction of highly selective ore volumes without presenting important slough/collapse events.

ACKNOWLEDGEMENTS

Sincere thanks you to Eng. Glauber Rosa Luvizotto for providing us with the required support to materialize this work.

Thanks also go to Geol. Leandro Ribes de Lima, Eng. Hugo Ribeiro de Andrade Filho, Eng. Nelson Munhoz, Mr. Jose Claudio Araújo, Eng. Edvaldo Barbosa, Ronair Vieira, Fabricio Rangel, Wanderson Dantas, Rodolfo Renó, Gabriel Dimitrov for the Constant support in the field.

REFERENCES

Bieniawski, ZT 1973, ‘Engineering classification of jointed rock masses’, *Transactions of the South African Institution of Civil Engineers*, vol. 15, no. 12, pp. 335-344.

Doblas, M 1998, ‘Slickenside kinematic indicators‘, *Tectonophysics*, vol. 295, pp. 187-197.

Dubé, B & Gosselin, P 2007, ‘Greenstone-hosted quartz-carbonate vein deposits’, in WD Goodfellow (ed.), *Mineral deposits of Canada: a synthesis of major deposit-types, district metallogeny, the evolution of geological provinces, and exploration methods*, Geological Association of Canada, St John’s, NL, special publication no. 5, pp. 49-73.

Grenon, M & Hadjigeorgiou, J 2003, ‘Evaluating discontinuity network characterization tools through mining case studies’, in PJ Culligan, HH Einstein & AJ Whittle (eds), *Proceedings of Soil and Rock America 2003*, Massachusetts Institute of Technology, Cambridge, MA, pp. 137-142.

Hayes, M & Hank, C 2008, ‘Evolving mechanical stratigraphy during detachment folding’, *Journal of Structural Geology*, vol. 30, pp. 548-564.

Mandl, G 2005, *Rock joints: the mechanical genesis*, Springer, Berlin.

Meló, M 2014, ‘Potvin stability graph applied to Brazilian geomechanics environment’, *Revista da Escola de minas de Ouro Preto*, vol. 67, pp. 413-419.

Palmstrom, A 2005, ‘Measurements of and correlations between block size and rock quality designation (RQG)’, *Tunnelling and Underground Space Technology*, vol. 20, no. 4, pp. 362-377.

Stewart, P 2005, ‘Minimizing dilution in narrow vein mines’, PhD thesis, University of Queensland.

Swart, AH & Handley, MF 2005, 'The design of stable stope spans for shallow mining operations', *Journal of the South African Institute of Mining and Metallurgy*, vol. 105, pp. 275-286