Underground Design Methods 2015 – Y Potvin (ed.)
© 2015 Australian Centre for Geomechanics, Perth, ISBN 978-0-9924810-3-2
doi:10.36487/ACG_rep/1511_08_Hassell

Dugald River trial stoping, overall hanging wall behaviour

R Hassell *MMG Limited, Australia*

R de Vries *MMG Limited, Australia*

J Player *MineGeoTech, Australia*

A Rajapakse *MMG Limited, Australia*

Abstract

Concerns regarding the uncertainty of stope dilution at MMG Limited's Dugald River Underground Mine led to a trial stoping program to acquire full-scale comprehensive geotechnical information and to test the validity of the proposed geotechnical and mining parameters. As part of the trial, a geotechnical instrumentation program was designed to improve the understanding of the rock mass response to the mining of the trial stopes. This included an array of instruments installed from dedicated hanging wall drives, hanging walls that included 66 multipoint borehole extensometers (MPBX), 23 time domain reflectometers, 24 geophones, six accelerometers and 15 observation holes.

Trial mining consisted of 19 sublevel open stopes with cemented rockfill (CRF) that extracted 335 kt of ore, with a panel height of 130 m and strike of 100 m. All stopes were monitored with a minimum of two MPBXs at the open span with a MPBX average density in the panel hanging wall of 180 m^2. The MPBXs were 19 m in length and consisted of six nodes. Instrument displacement information was recorded every 30 minutes by dataloggers to a resolution of 0.12 mm. This provided a high quality, detailed and extensive rock mass response to stope extraction.

The displacements were interpreted as hanging wall relaxation and shear on structure from specific stope firing and expansion of the mining front. Rock mass creep was also recorded in the hanging wall. The mechanism of displacement consisted mainly of strike-slip movement on high angle bedding and faults that are orientated sub-parallel to the dip of the orebody.

Overall hanging wall behaviour was assessed by investigating the near (stope hanging wall boundary to 6 m) and far (>6 m from stope boundary) displacements as the sequence progressed. The primary rock mass response stage was the extraction of the crown pillar. The secondary responses were associated with the cable bolt arrays mitigating some of the deformation of the hanging walls with more movement mid-span compared to the cable bolt horizon. Finally, the displacement results post-filling showed the backfill mass was being slightly compacted by ground movement.

1 Introduction

The Dugald River Zn-Pb-Ag deposit is located 85 km northwest of Cloncurry, Queensland. The deposit was discovered pre-1880, with first systematic exploration not occurring until the 1950s. It is regarded as one of the largest and highest-grade known undeveloped deposits of zinc, lead and silver in the world with a total mineral resource (measured, indicated and inferred) of 55 Mt at 13.4% zinc, 2.1% lead and 36 g/t silver (MMG Limited 2014). The deposit was acquired by MMG Limited in 2009, with development of exploration declines at the site commencing in February 2012. Exposure of the geological conditions during development identified a more complex and challenging mining environment than previously assumed, making the original mine plan difficult to achieve. A mining method review completed in 2013 recommended a trial stoping program to confirm the new proposed mining method and practical operating parameters. Trial stoping commenced in early 2014.

As part of the trial, a comprehensive geotechnical instrumentation programme was designed to improve the understanding of the rock mass response to the mining of the trial stopes. This included an array of 119 instruments installed adjacent to the trial stope hanging walls. Instrumentation was installed in diamond drill holes, drilled from dedicated hanging wall instrumentation drives. An additional benefit of the high density drilling is that it enabled a step change in the understanding of the lithological and structural information for the trial stoping area.

2 Geology of Dugald River

The Dugald River deposit occurs within the eastern fold belt of the Mount Isa Inlier and the Dugald Lode is hosted within a steeply dipping black slate sequence of low metamorphic grade. The deposit is a steep dipping tabular orebody, extending approximately 2 km along strike and to a depth of approximately 1 km. The orebody strikes approximately north–south (Mine Grid North), dips between 45 to 85° to the west, and varies in true thickness from 1 to 35 m. The area of greatest ore thickness occurs in the central part of the orebody between the depths of 300 and 600 m, which coincides with the area of flattest dip.

The hanging wall slates (HWSL) occur in the immediate hanging wall of the Dugald Lode and typically vary in thickness between 50 and 100 m. In the area where the Dugald Lode dip flattens to less than 50°, the thickness can be as little as 10 m. Muscovite schist, mafic porphyry and calc-silicates units are to the west of the hanging wall of the HWSL. The HWSL typically consist of massive, fine-grained dark grey slate, spotted in places; to laminated, fine-grained dark grey to light grey slates, often with carbonate veining.

The footwall slates and limestones are to the footwall of the Dugald Lode. A narrow zone of footwall slates (FWSL) grade to limestone (LMST) over a distance of up to 50 m. In some areas, the footwall slates are absent and the limestone forms the footwall contact with the Dugald Lode. The footwall slates are almost identical in geological and geotechnical parameters to the hanging wall slates.

The orebody is hosted by slate and is dominated by sphalerite and pyrrhotite/pyrite with minor galena, arsenopyrite and chalcopyrite. It ranges from massive sulphide breccias with large angular clasts of slate to stringer veins hosted in slate (Hassell et al. 2015).

3 Geotechnical conditions

The understanding of the geotechnical environment at Dugald River evolved as more detailed information became available during development of the exploration declines, and subsequent diamond drilling. The original geotechnical domain model assumed a continuous single structure, termed the hanging wall shear zone (HWSZ) which varied in thickness and distance from the orebody hanging wall. The selection of the trial stoping area was based on the drilling information available at the time. As such, it was seen to be representative of the likely hanging wall rock mass conditions expected across the orebody in 2013. However, due to the tight infill drilling completed for the hanging wall instrumentation program, a more detailed and comprehensive geotechnical knowledge of the hanging wall rock mass was obtained. This additional information changed the geotechnical understanding from the original model.

The hanging wall rock mass consists of a steeply west dipping, bedded rock intersected by large-scale, potentially weak, geological discontinuities. Some of these features are sub-parallel to the orebody and sometimes located within the orebody or the immediate hanging wall of the designed stopes. Other structures are shallower dipping and crosscut the lithology. A cross-section showing major fault locations is provided in Figure 1. Structure conditions are generally smooth to slickensided with graphite or chlorite infill. The weak structures are variable along strike and down dip, even within a single stope geometry (i.e. 20 m along strike). The rock mass outside of the geological structures can be rated as fair to good, as indicated by the low frequency of discontinuities per metre and the high strength of the intact rock (Carswell et al. 2015). Average UCS of the massive/breccia orebody is approximately 200 MPa. The strength of the host rock slates is about 150 MPa with both rock masses having a high modulus (Hogan & Thompson 2014). The area selected for trial stoping at Dugald River is located at shallow depth less than 250 m below the ground surface. In situ stress measurements have shown similar stress magnitudes and orientations as other measurements in the Mount Isa Inlier, namely a north–south orientated σ_1 and a sub-vertical σ_3 (Mining Measurement Services Pty Ltd 2014a; Mining Measurement Services Pty Ltd 2014b).

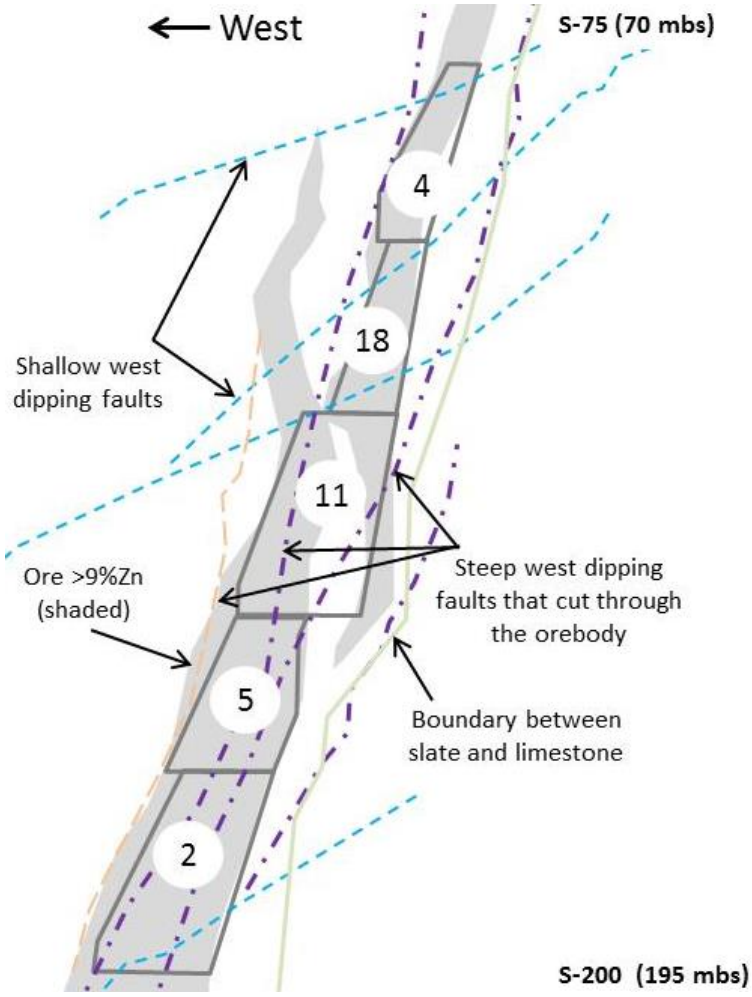

Figure 1 **Cross-section through the trial stopes showing major fault orientations (Carswell et al. 2015)**

4 Trial stoping

The objective of the trial stoping program was to obtain additional geotechnical information and to test the validity of proposed geotechnical and mining parameters. The trial area was chosen due to its relevance in evaluating the following rock mass responses to excavation:

- Examine the hanging wall response, particularly the faults in close proximity to the hanging wall of the stopes.
- A crown mid-way through the sequence to examine undercutting effects and backfill performance.
- Transverse and longitudinal stope geometry performance.
- Fractured ore due to faulting and handling internal stope dilution.
- The effect of faulting on stope crown stability.

Mining of the trial stopes was by sublevel open stoping (SLOS) with CRF. Sublevel heights were 25 m and stope strike lengths varied from 15 to 30 m. A total of 19 stopes were taken during the trial for a total of 335 kt of ore. A long section of the trial area is shown in Figure 2. Due to the variability in the lode width both longitudinal (<12 m width) and transverse stopes (>12 m width) were designed.

It is proposed that the Dugald River orebody is to be mined as multiple panels in a bottom up, continuous sequence, retreating to a crown pillar. To simulate this in the trial stoping area, the S-100 Level stopes were mined and filled early in the sequence with the remaining sequence starting at the S-200 Level. As the dilution from the early stopes was favourable, stopes later in the sequence were expanded along strike (Stopes 8, 11, 13, 14, 18, 19), up dip (Stope 15) or both (Stopes 16 and 17).

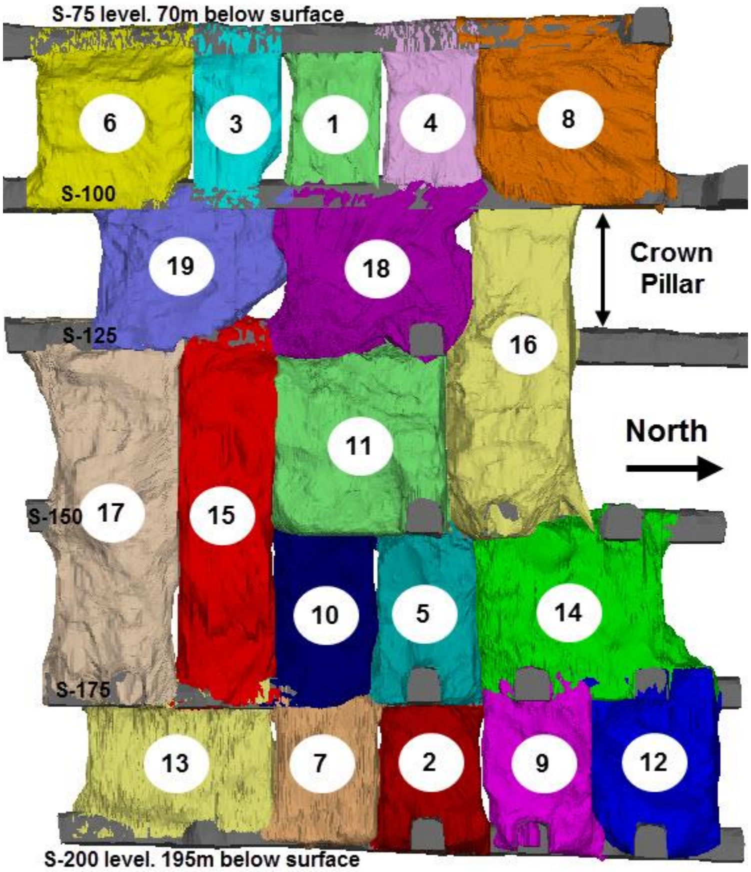

Figure 2 Longitudinal section showing trial stopes and mining sequence

5 Hanging wall instrumentation program

The following section provides a brief description of the instrumentation layout and operational aspects. A more detailed description, including the design and installation requirements, is provided in Carswell et al. (2015).

The main objectives of the hanging wall instrumentation program were to:

- Monitor the hanging wall rock mass response to trial stoping. Including measurements and location of displacement. Identify the structures and the mechanisms driving the displacement.
- Investigate the effect of stope size and sequence on rock mass response.
- Determine the effectiveness of hanging wall stope cable bolting.
- Measure the hanging wall rock mass response post backfilling.

The hanging wall monitoring instruments were installed from three dedicated hanging wall instrumentation drives at the S-100, S-150 and S-175 Levels. The levels provided adequate coverage utilising both up and down holes. The instruments were connected to three dedicated dataloggers, one on each level, which collected high resolution readings (0.12 mm) every 30 minutes.

The program utilised a variety of instruments which are summarised below:

- 66 × 19 m length SMART MPBXs. Six anchors spaced at 12.0, 14.0, 16.0, 17.0, 18.0 and 19.0 m from instrument head. Installed on an average density in the hanging wall of 180 m^2.
- 15 × hanging wall observation holes.
- 23 × TDRs (4.95 mm diameter). Installed in combination with the 19 m length SMART MPBX. The results from the TDRs were limited in detail, and did not offer the resolution that the MPBX results provided.

A typical section through the trial stoping area with the instrumentation layout is shown in Figure 3. The 19 m length SMART MPBXs were installed with the last anchor (Anchor 1) being 1 m from the design stope hanging wall.

In addition to the displacement monitoring, stope blast vibration monitoring was undertaken from 24 triaxial geophones and 6 triaxial accelerometers located within the hanging wall displacement instrument array. The results of this program are discussed in Hassell et al. (2015).

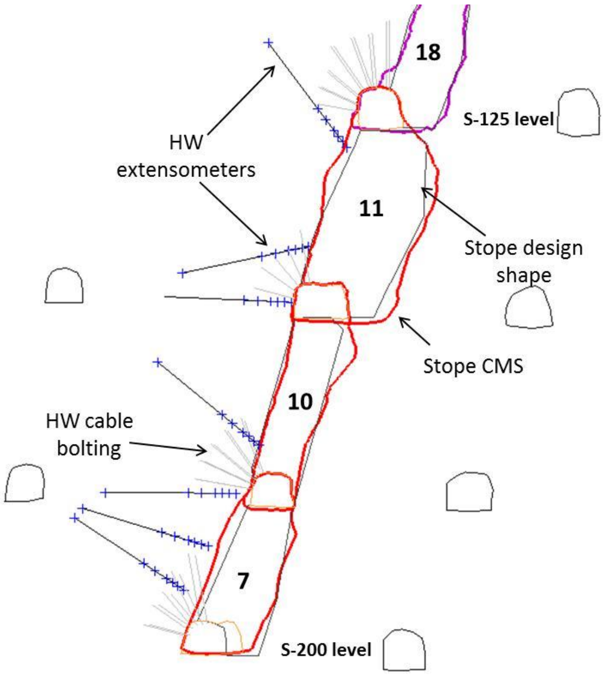

Figure 3 Section through the trial stoping area showing typical instrument layout. Crosses identify the anchor locations. Stope design and CMS shapes are shown

6 Individual instrument results

Of the 66 SMART MPBXs installed, only 56 provided good quality results, with the remainder either being damaged or had poor encapsulation during grouting. These have been omitted from any further analysis. The instruments were not all installed and operational at the same time, with progressive installation occurring that tracked the stoping sequence. All instruments were installed before the firing of Stope 9. There was a delay in connecting the dataloggers to the instrument arrays during which hand held measurements were taken. The resolution of the hand held measurements was 1.2 mm and recorded at various times (daily to weekly) against the datalogger resolution of 0.12 mm with readings taken every 30 minutes. When operational, the datalogger data was downloaded regularly and transferred to a database where site specific excel macros were developed to plot and analysis the data.

A typical MPBX response is shown in Figure 4. The displacement shown is the total movement between the head and the relevant anchor, with Anchor 1 (located furthest from the head) always showing the most movement and Anchor 6 the least. Displacements between anchors are determined by subtracting the displacement of the next closest anchor to the head. The S-100-HW-E3-B instrument was installed in the lower hanging wall of Stope 3, which is located above the crown pillar. Initial readings were from the hand held unit, hence the lack of resolution particularly at low levels of displacement. A small response (1 mm) to mining was seen following the firing of Stope 3 with no further displacement observed until the extraction of the underlying Stope 19. This generated a larger response particularly between Anchors 4-5 (~5.5 mm) which coincided with the location of a steep west dipping fault. Displacement is characterised by a large movement in the immediate aftermath of the stope mass blast followed by rock mass creep, which continued for a couple of weeks before levelling out. This profile of displacement (large displacement immediately after firing followed by creep) was regularly observed.

Generally the largest displacements were recorded when the instrument was located in the hanging wall of the stope being fired, with the larger firings (stope mass blast) producing the greater movements compared to smaller firings (winze, slot undercut). However, it was observed that displacement continued, typically at a smaller magnitude following backfilling due to firing of adjacent stopes. Only very minor displacements were observed in areas that had yet to undergo stoping.

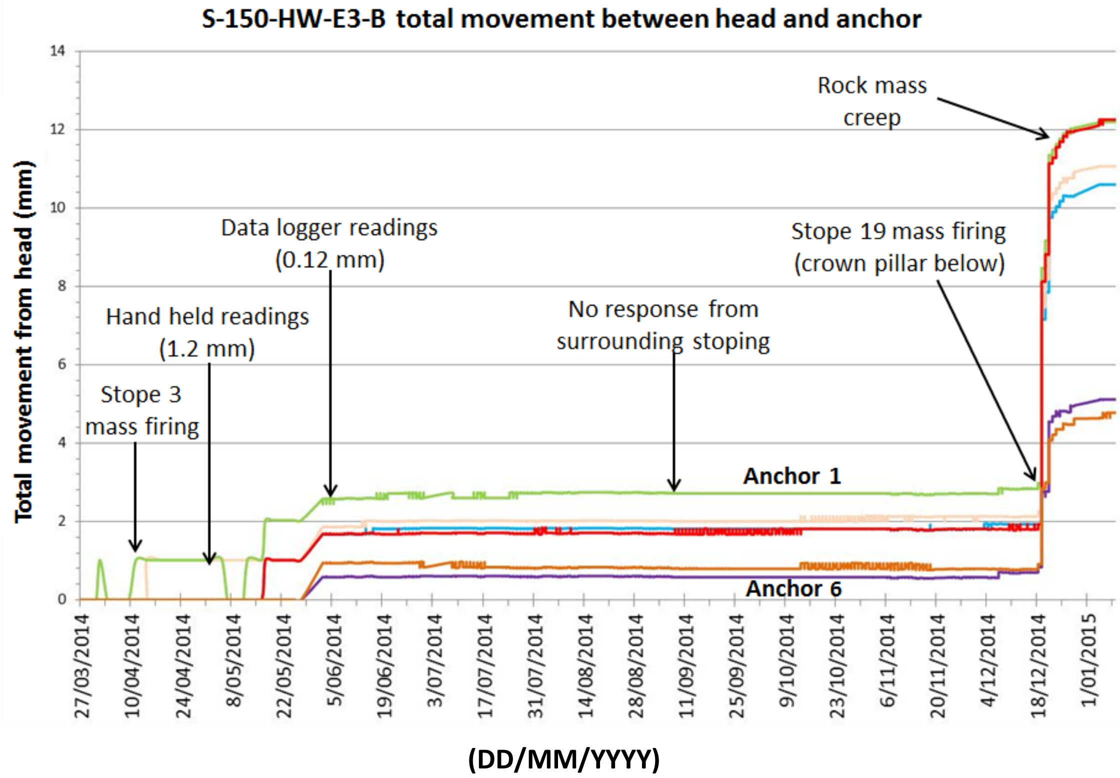

Figure 4 Extensometer results for the instrument installed in the hanging wall of Stope 3 showing minor initial movement after stope firing (10 April 2014) but with a significant increase after firing the underlying crown pillar stope (18 December 2014)

6.1 Mechanism of displacement

Where displacement was measured along an extensometer, the borehole observations and diamond drill core would be reviewed to determine the mechanism of displacement. This process established the mechanism of displacement consisted mainly of strike-slip movement on high angle bedding and faults, which are orientated sub-parallel to the dip of the orebody. This movement has been observed in a number of hanging wall observation holes, with an example shown in Figure 5. This movement agrees with the mining induced stress regime with loss of confinement in the east–west direction allowing unclamping of the structures combined with a north–south σ_1 enhancing the strike slip motion. Structures varied in size ranging from mm thickness up to large zones of broken ground.

The extensometers were installed as close to perpendicular as practical to the main planes of movement. As the movement has been observed to be majority strike slip, the measured displacements are apparently underestimating the actual displacement along the structures.

Figure 5 Image from borehole camera surveys of an observation hole showing pre-stoping condition and shear movement along a pre-existing structure post stoping

7 Hanging wall response to mining

Combining all of the displacement data recorded over the trial stoping time line gave an overall hanging wall displacement of 2,915 mm for 56 instruments which equates to an average of 52.1 mm per instrument. However, this displacement includes instrument nodes that have failed into a stope. Failed nodes can record displacement as high as 440 mm. When this data is included in the analysis it obscures the more subtle global hanging wall response.

A more accurate understanding of the global measurements is provided when the nodes that failed into the stope are manually changed back to the reading prior to failure. This essentially will provide hanging wall response prior to the stope failure. This produces an overall hanging wall displacement of 862 mm or an average of 15.4 mm per instrument.

7.1 Hanging wall response to stope firings

The review of individual instruments showed the direct rock mass response to stope mass blasts. To provide a greater understanding of the magnitude and location of the overall hanging wall deformation, contouring of the displacement was undertaken. This aids in identifying spatial relationships and the influence each firing had on the surrounding rock mass. Figure 6 are contour plots of displacement following the firings of Stopes 15 and 16 respectively. Hard boundaries to limit data crossover have been set between mined out areas and unmined rock.

The largest displacements for both firings are centred within the mined stope outline. Displacements then quickly reduce outside this zone with displacements constrained to the previously mined out areas only. No movement is seen in unmined rock. Generally, the displacement response in the previously mined hanging wall is larger in extent along strike than down/up dip, this could be a result from the hanging wall cable bolting along each level. The crown pillar in the case of Stope 15 firing is working to limit displacement above the pillar in the S-100 stopes. The start of the extraction of the crown pillar (Stope 16) has increased the magnitude of deformation and location, with deformation occurring in the S-100 stopes but only directly up dip of Stope 16.

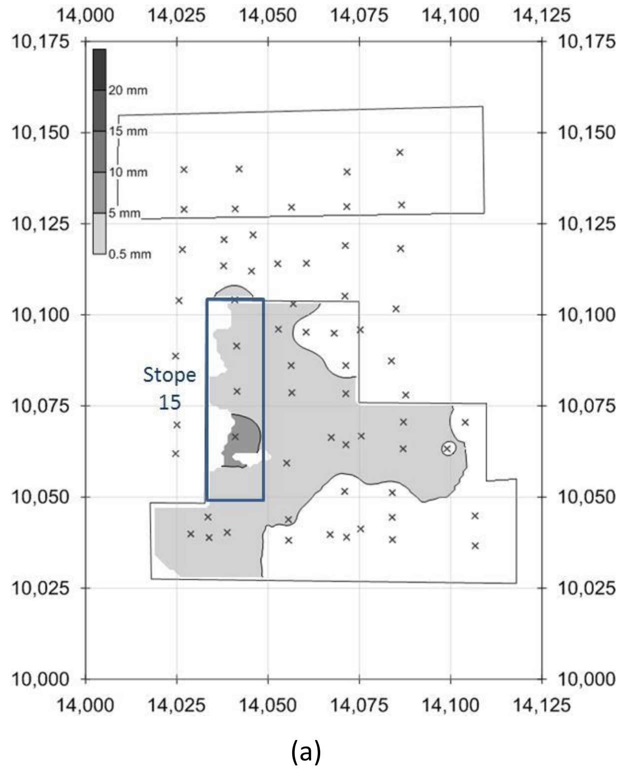

Figure 6 Longitudinal view of the hanging wall showing displacement contours for the 24 hours after (a) Stope 15; and (b) Stope 16 firings. Nearest extensometer anchor location to the stopes are identified as an ×, x-axis is Northing and y-axis is RL

7.2 Global displacement by hydraulic radius

The hydraulic radius of the combined mined stopes has been calculated after the extraction of each stope in the sequence. The S-100 Level stopes have been ignored in the calculation until the stope crown is mined, then only the stopes directly up dip of the crown pillar extracted stope are included in the calculation. This takes into account the influence the remaining crown pillar has on restricting displacement on the immediate up dip S-100 Level stopes.

The hydraulic radius has been graphed against the cumulative displacement, and is shown in Figure 7. Total displacement, near field displacement and far field displacement is displayed. Total displacement is the combined displacement measured along the entire instrument. Near field displacement is displacement measured between Nodes 1-4 only. This extends 6 m from the stope hanging wall and can be considered the section of the hanging wall likely to contribute to stope dilution. Far field displacement is the displacement measured between Nodes 5 and the head. Approximately, 70% of the total displacement is classified as near field.

A sharp increase in displacement is seen between a HR of 15.8 and 16.2 for both the near and far field results, this is despite it being a relatively small change in the hanging wall profile. This change denotes the first firing of a stope in the crown pillar (Stope 16). Post this, the magnitude of displacement for the following firings is much larger than the pre-crown pillar mining. This is more clearly indicated in Table 1 which shows the displacement measured between each stope firing as percentage of the total movement. Stoping prior to stope 16 only accounted for 42% of the far field and 43% of the near field displacement. Mining of the remaining four stopes, three of which are part of the crown pillar, accounted for greater than 50% of hanging wall displacement. Interestingly, Stope 17, which was not a crown pillar stope but was mined after the first crown pillar stope was extracted, produced 18% of all near field displacement; double of any other stope that was not part of the crown pillar.

The overall results show increasing rates of displacement as the stope sequence progressed and the overall hanging wall span was progressively opened. However, there is marked increase in displacement, both in the near and far field after the crown pillar is broken. This has implications for the broader stoping sequence to be used at Dugald River. It is accepted that there was non-uniform distribution of extensometers, which could be distorting the displacement measurements in the last part of the stoping sequence.

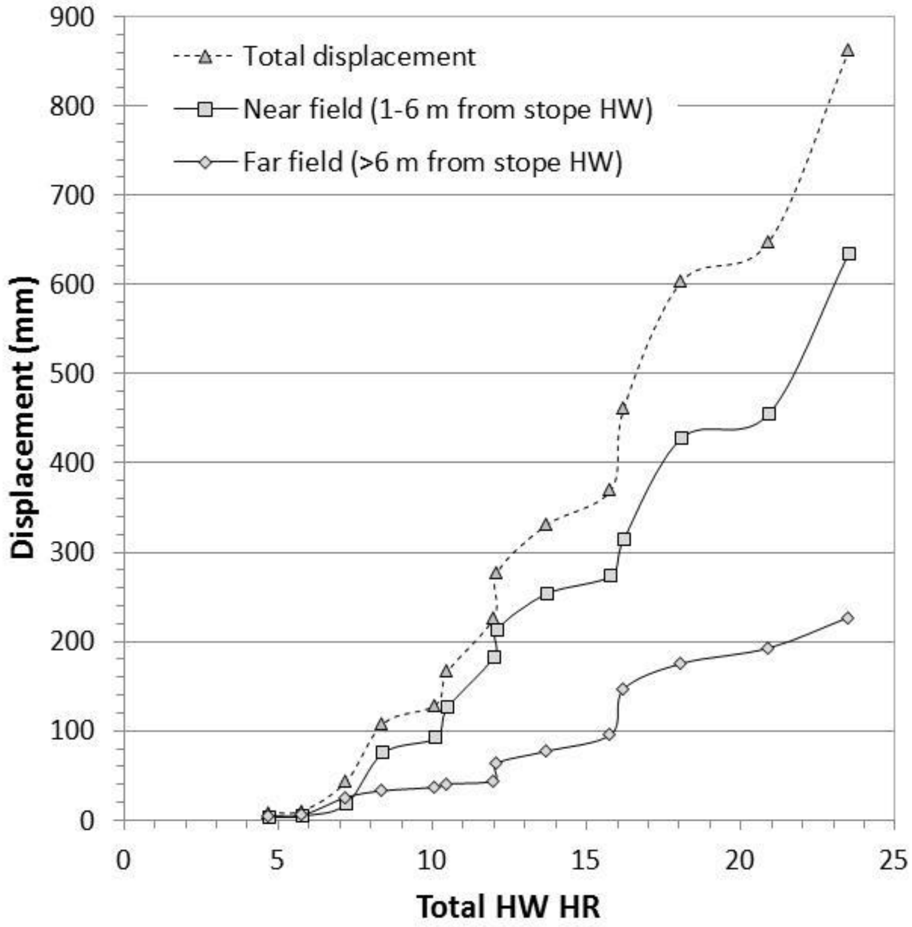

Figure 7 Graph showing cumulative displacement from hanging wall extensometers 6 m from the hanging wall (Nodes 4-0) and greater than 6 m from the hanging wall (Nodes head-5). Crown pillar extraction occurred at HR 16.2

Table 1 Hanging wall displacement with increasing hydraulic radius

Stope	Date final mass firing (2014)	Hydraulic radius	Number of extensometers operational	Displacement between mass firings — near field (mm)	Near field displacement as % of total	Displacement between mass firings — far field (mm)	Far field displacement as % of total
2	10.04	4.7	10	3.5	0.4	4.9	0.6
5	08.05	5.8	22	1.2	0.1	1.0	0.1
7	07.06	7.2	43	13.0	1.5	19.6	2.3
9	02.07	8.4	56	57.6	6.7	7.4	0.9
10	13.07	10.1	56	16.7	1.9	4.0	0.5
11	31.07	10.5	56	34.2	4.0	3.6	0.4
12	20.08	12.0	56	56.9	6.6	3.7	0.4
13	05.09	12.1	56	30.5	3.5	19.7	2.3
14	22.09	13.7	56	39.9	4.6	13.3	1.5
15	04.10	15.8	56	20.4	2.4	19.2	2.2
16 (+8)	01.11	16.2	56	40.6	4.7	50.4	5.8
17	23.11	18.1	56	114.0	13.2	28.9	3.4
18 (+4+1)	03.12	20.9	56	26.5	3.1	17.0	2.0
19 (+3+6)	21.12	23.5	56	179.9	20.9	34.6	4.0

8 Influence of cable bolting

Hanging wall cable bolts were installed along the entire span of the trial stoping area from oredrives located on the hanging wall of the orebody contact. They consisted of twin strand, bulbed cables, plated where the cable collar was not located in the blasthole ring design. Toe spacing's were approximately 3.0 by 2.5 m in the general arrangement shown in Figure 3.

Individual extensometer results show a number of examples where the cable bolt array was seen to be limiting the amount of displacement in the hanging wall (Carswell et al. 2015). This occurred in the same plane perpendicular to the stope hanging wall and in similar rock mass conditions. The extensometers installed outside the influence of the cable bolt array had a higher displacement than those within the cable bolt zone of influence.

The combined data set was separated into those instruments influenced by the hanging wall cable bolting array, and those that were installed mid span (no influence). Extensometer movement associated with stope dilution (nodes failed into stope) is critical to understanding what affect the cable bolts have on restricting rock mass movement and was included. However, when an anchor fails it can read up to 440 mm of movement, which over 1 m is excessive and well beyond the limit of the rock mass or cable bolt to withstand. To include what is regarded as acceptable movement for failed anchors, a maximum strain of 5% was used (50 mm movement for 1 m anchors, 100 mm movement for 2 m anchors). Beyond this strain the rock mass is expected to fail into the stope and cable bolts would be expected to yield.

The data was further separated into near (<6 m) and far field (>6 m) displacement, near field is directly influenced by the cable bolt arrays. As shown in Figure 8, there is an increase in the overall displacement for instruments that are not influenced by cable bolts, 598 mm compared to 325 mm for those within the cable arrays. When the data is divided by the number of instruments it shows 12 mm of movement per instrument for those within the cable array, and 20.6 mm of movement per instrument for those mid span. This indicates that the hanging wall cable bolts are reducing the level of near field displacement by an average of 40%, demonstrating the benefit of cable bolts in stabilising the hanging wall rock mass. This benefit did not start to occur until after the mining of Stope 12. Before this, it appears the level of hanging wall displacement was not sufficient to mobilise the cable bolts. During the crown pillar extraction the cable bolts can be seen to offer the greatest advantage in limiting deformation in the hanging wall.

A similar but reduced trend is seen in the far field displacement with those instruments not influenced by the cable bolt array having a 20% higher displacement per instrument.

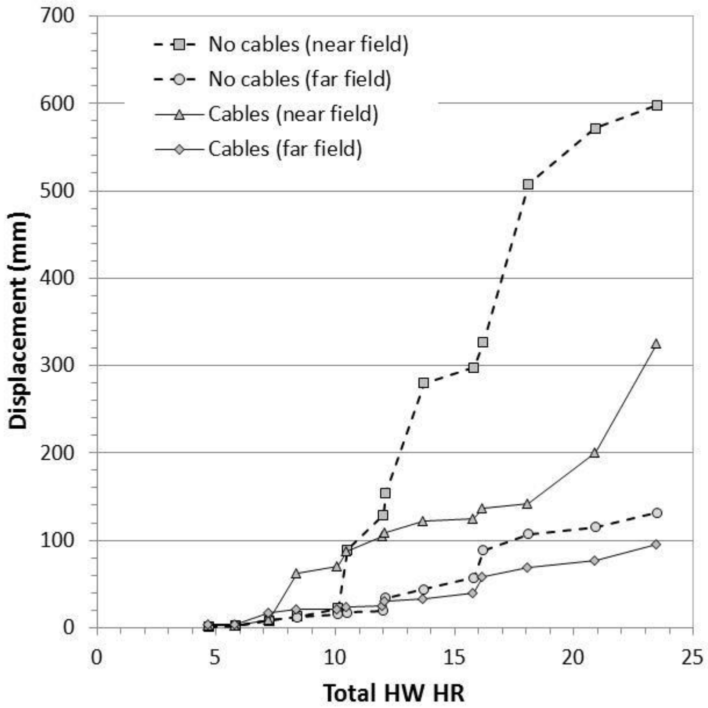

Figure 8 Graph showing cumulative displacement influenced by the cable array (cables) and those not influenced by the cable array (no cables). Where failure has occurred between nodes, 50 mm displacement has been used

9 Hanging wall closure post-backfilling

Backfilling of stopes began immediately after the stope had been emptied and was completed within 2-7 days depending on the size of the stope. The impact of backfill on the hanging wall movement can be seen in Figure 9, which displays the result of an extensometer located in the hanging wall of Stope 11. Large increases in displacement is induced after the stope firings followed by an extended time of rock mass creep. In this example, the extensometer was located within the cable bolt array with overbreak occurring above the cable bolts. It appears the cable bolts are limiting but not stopping the displacement, hence the rock mass creep, which continues until the backfill reaches the same height in the stope hanging wall as the extensometer, after which displacement stops.

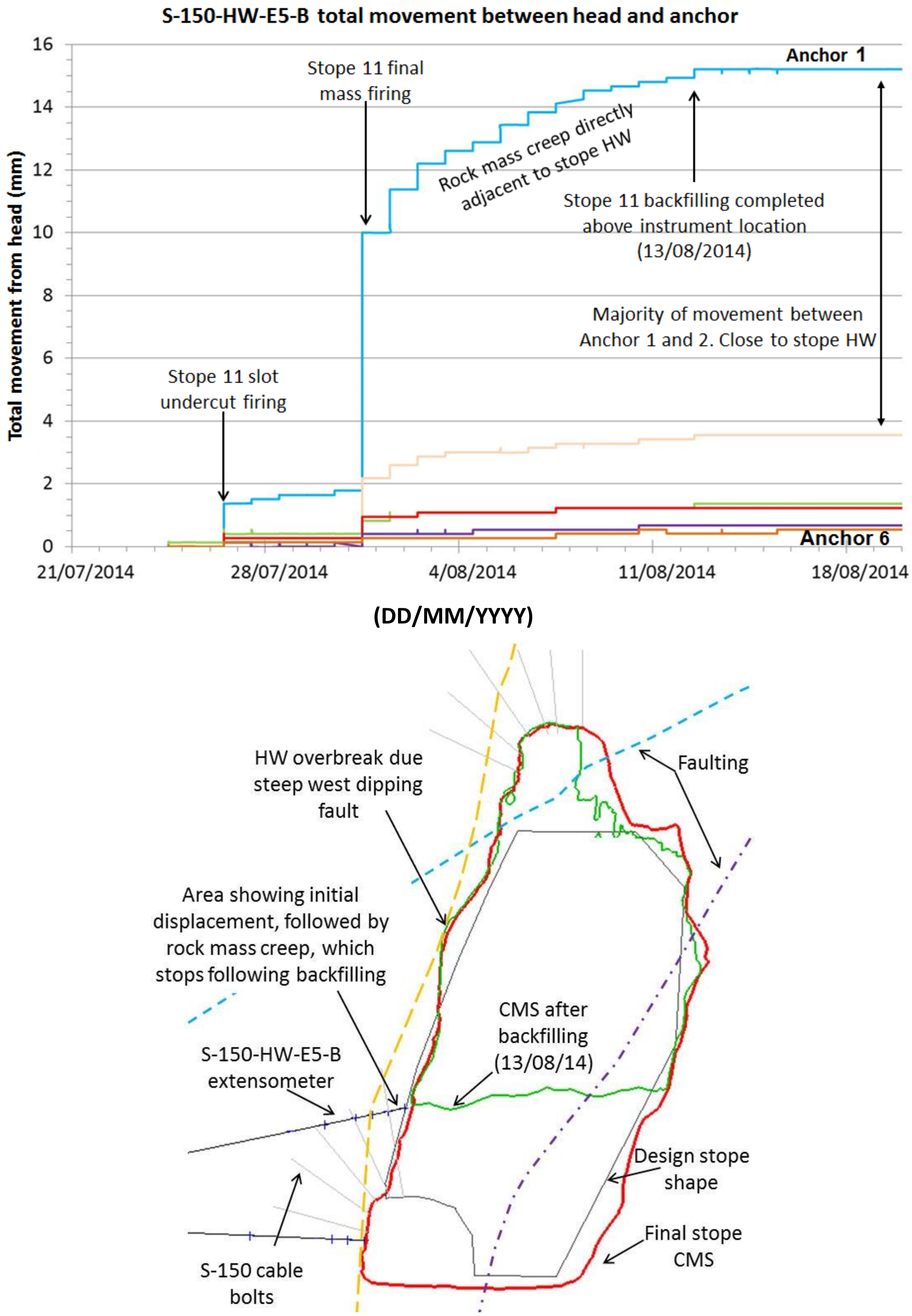

Figure 9 Extensometer response to mining Stope 11 and cross-section through Stope 11 showing the location of the extensometer

Backfill was observed to limit movement once placed; however, further mobilisation of the hanging wall post-backfill was also identified following adjacent stope firings. The magnitudes of displacement were relative to the distance from the firing. Modifying the overall hanging wall displacement data to show only displacement after the backfilling of the stope, provides a post-backfill displacement of 236 mm which is

27% of the overall displacement (862 mm). Graphed against hanging wall hydraulic radius the post-backfill displacement data (Figure 10) shows a similar trend to the previously discussed overall displacement (Figure 7), with an increase in the rate of displacement after the first crown pillar stope is extracted. Approximately 50% of the displacement occurred after this stage of mining, and for the far field hanging wall it was approximately 70%. By the end of the trial stoping the amount of displacement for both the near and far field was similar, indicating that a higher proportion of post-backfilling movement occurs deeper in the rock mass compared with pre-backfilling movement.

An estimate of the amount of closure on the backfill can be calculated by assuming an average stope mining width of 10 m. Given the measured 236 mm of displacement, this provides an average closure of 0.02% strain.

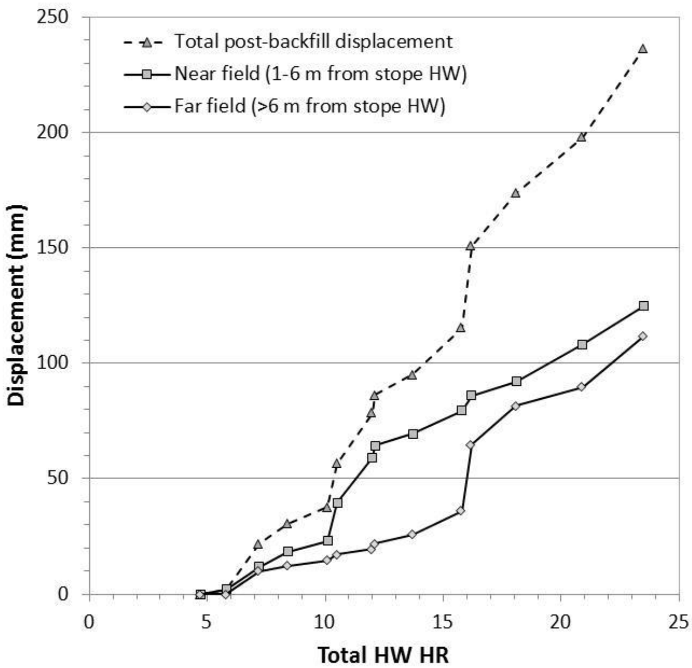

Figure 10 Graph displaying cumulative displacement post-backfilling

10 Discussion on results

Hanging wall rock mass behaviour during trial stoping was intensively studied and was found to be dominated by the frequency and location of the hanging wall structures which ranged from millimetre thickness faults to large zones of broken ground. Structure condition was a secondary consideration as the majority of structures were smooth and graphite filled. Previous geotechnical models focussed primarily on larger structures (hanging wall shear zone model), the updated geotechnical dilution model now incorporates the effect of smaller structures. Onsite geotechnical core logging procedures have been updated to improve capturing of this data.

The displacements were interpreted as hanging wall relaxation and shear on structure as was shown on the bore hole camera descriptions, due to the combined influence of specific stope firing and continued expansion of the mining front. Rock mass creep was also recorded in the hanging wall. The mechanism of shear displacement consisted mainly of strike-slip movement on high angle bedding and faults that are orientated sub-parallel to the dip of the orebody.

Overall hanging wall behaviour was assessed by investigating the near (stope hanging wall boundary to 6 m) and far field (>6 m from stope boundary) displacements as the stope sequence progressed. This identified key stages in the sequence for rock mass response. Individual stope sizes appear to have a less effect compared to the overall sequencing. The crown pillar acts to restrict hanging wall movement. This is significant as it identifies when a step change in the rock mass response will occur. Similar responses are expected when the crown pillars of each panel are broken. By taking the crown pillar as part of the continuous sequence it is expected to create a hanging wall response of earlier but smaller displacement, compared to leaving the crown pillar till the end of the panel. This alternative method (delayed crown extraction) may provide an improved rock mass response prior to the crown stopes being mined, but is expected to cause significantly more displacement when the crown pillar is extracted. This would create difficulties for crown pillar extraction leading to additional ore loss.

The cable bolt arrays were mitigating some of the deformation of the hanging walls with more movement mid-span compared to the cable bolt horizon. The cable bolt arrays offered more benefit in restricting displacement around the crown pillar location opposed to levels located below. This provides guidance to optimising stope reinforcement in terms of hanging wall cable bolt density against expected deformation.

Hanging wall displacement post-backfilling continued but with a lower magnitude of movement that is still controlled by the overall span and highly influenced by the extraction of the crown pillar. A higher proportion of movement occurred deeper into the rock mass. Three potential backfill failure modes are considered possible; shearing through the backfill, crushing (compression) and tensile failure (unravelling when undercut). For the measured strain (0.02%); which is slightly compacting the CRF mass the likely backfill failure mechanism is expected to be unravelling due to the lack of confinement, which has implications for backfill design strengths.

11 Conclusion

The geotechnical hanging wall monitoring program completed as part of the Dugald River trial stoping program was designed to improve the understanding of the rock mass response to mining. The program was comprehensive and significant in scale. This allowed for a global examination of hanging wall displacement that identified key stages in the mining sequence where the rate of response increased. The benefit of cable bolts was confirmed and post-backfilling closure identified.

The information has been used in the updated Dugald River development plan by: improving stope dilution estimates, confirming the benefits of the global sequence, supporting stope cable bolt densities, understanding potential backfill failure modes and, importantly, providing a higher level of confidence in the geological conditions.

Acknowledgement

The authors would like to acknowledge Tom Williams and Jack Carswell from MMG Limited's Dugald River Mine Geotechnical Department and Rowland Whiting from MineGeoTech for their contribution to this project. The authors would also like to thank MMG Limited for permission to publish the paper.

References

Carswell, JF, Player, J, de Vries, R & Hassell, R 2015, 'Cross-section through the trial stopes showing major fault orientations', figure, in PM Dight (ed.), *Proceedings of the Ninth International Symposium on Field Measurements in Geomechanics, Australian Centre for Geomechanics*, Perth.

Hassell, R, Villaescusa, E, de Vries, R & Player, J 2015, 'Stope blast vibration analysis at the Dugald River underground mine', *Proceedings of the 11th International Symposium on Rock Fragmentation by Blasting (Fragblast 11),* The Australasian Institute of Mining and Metallurgy, Melbourne.

Hogan, P & Thompson, A 2014, *Report on Intact Rock Properties Testing,* report, prepared for Western Australian School of Mines, Kalgoorlie.

Mining Measurement Services Pty Ltd 2014a, *MMG Limited, Dugald River Project south decline, south 220 access rock stress measurment,* report, Mining Measurement Services Pty Ltd, Macclesfield.

Mining Measurement Services Pty Ltd 2014b, *MMG Limited, Dugald River Project south decline, SP6 rock stress measurements, report,* Mining Measurement Services Pty Ltd, Macclesfield.

MMG Limited 2014, *2014 Mineral Resources and Ore Reserves Statement,* MMG Limited, Melbourne, viewed 15 June 2015, http://www.mmg.com/en/About-Us/Mineral-Resources-and-Ore-Reserves.aspx