Measurement and Modelling of Blast Movement to Reduce Ore Losses and Dilution at Ahafo Gold Mine in Ghana*

E. Engmann, S. Ako, B. Bisiaux, W. Rogers and S. Kanchibotla

Engmann, E., Ako, S., Bisiaux, B., Rogers, W. and Kanchibotla, S. (2013), "Measurement and Modelling of Blast Movement to Reduce Ore Losses and Dilution at Ahafo Gold Mine in Ghana", *Ghana Mining Journal,* pp. 27 - 36.

Abstract

Blast induced rock mass displacement can have a significant impact on grade control. The mischaracterisation of the grade boundaries without proper understanding of blast movement can lead to significant financial losses in terms of ore losses and dilution. Ore dilution occurs when waste material is miscategorised as ore and sent for processing diluting the run of mine head grade and recovery. Ore losses take place when valuable mineral is miscategorised as waste and sent to the waste dumps. The geologists at Newmont Ahafo Mine have realised the impact of blast movement on ore losses and dilution and have implemented a blast movement study to minimise blast induced ore losses and dilution. This paper describes the application of the latest measurements and modelling techniques in understanding the blast dynamics and develops site specific solutions to minimise blast induced dilution and ore losses. These solutions are validated at Newmont Ahafo open pit mine through systematic trials and subsequently incorporated into site standard operating procedures to sustain the benefits.

1 Introduction

Newmont Ahafo mine is situated in the Brong Ahafo Region of Ghana near the towns of Kenyase and Ntotoroso about 290 km northwest of the Ghanaian capital city of Accra (Fig 1). Mining operations commenced in January 2006 and currently has four active pits (Apensu, Subika, Awonsu and Amoma). Processing is by conventional mill and carbon-in-leach circuit. Reserves are currently estimated at 147.3 Mt at 2.11 g/t (~10 Moz) with potential for growth both from new discoveries and the development of Subika underground operation. The average annual production stands at 54 Mt (10.8 Mt of ore and 43.2 Mt of waste). Due to the limiting capacity of the mill, only 7.5 Mt out of the 10.8 Mt of ore are processed while the remaining 3.3 Mt are stockpiled.

In 2007 and 2008, Ahafo mine used bamboo sticks and poly pipes to measure blast movement and realized that the procedure is unreliable when making ore block adjustments for blast movements. The mine therefore commissioned a blast movement study as part of a lean six sigma black belt project to Minimize Ore Losses and Dilution (MOLD) which has a broader scope (sampling – ore control model – blasting – excavation). The project started in November 2010 and was completed in 2011 by JK Tech Pty Ltd, Australia.

Extensive research has been conducted at the University of Queensland, Australia over the last 15 years to understand the impact of blast movement on ore losses and dilution. Recent outcomes of this research have developed innovative tools and techniques to measure and model blast movement.

A methodology, developed by JKTech Pty Ltd, using these techniques to minimise ore losses and dilution in open pit mines is shown in Fig. 2.

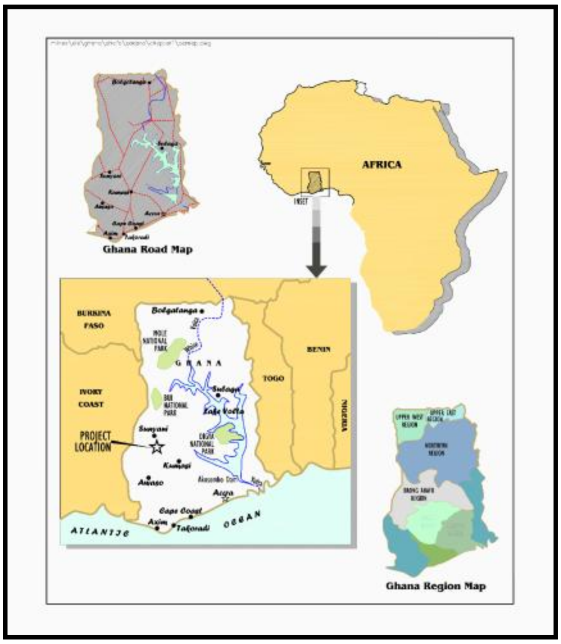

Fig. 1 Newmont Ahafo Mine Location

* *Manuscript received February 27, 2012*
Revised version accepted November 5, 2012

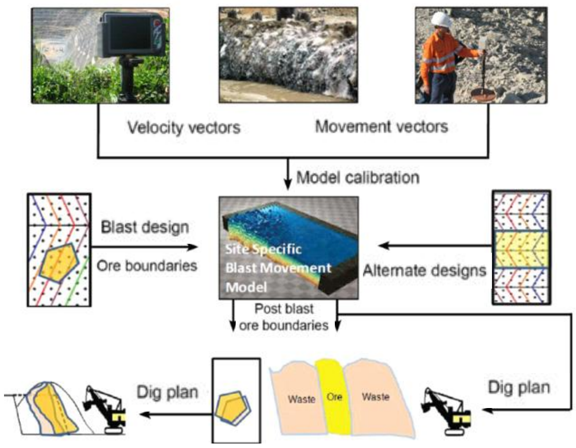

Fig. 2 Methodology to Minimize Ore Losses and Dilution

This comprehensive method is summarised as follows:

1. Understand the dynamics of blast movement with comprehensive monitoring using high speed video and blast movement markers.
2. Develop site specific models to predict the extent of movement within the blast and its impact on grade control.
3. Develop alternative strategies to minimise ore losses and dilution.
4. Validate the alternative strategies with controlled trials and then incorporate them into standard operating procedures to sustain the gains.

This paper explains in detail each step of the methodology (measurement, modelling, alternative strategies and validation), its application at Ahafo mine and how it was used to develop site specific solutions to minimise blast induced dilution and ore losses.

2 Blast Movement Trials

2.1 Setup

A total of 5 trial blasts, 3 in Apensu pit and 2 in Awonsu pit, were monitored between November 2010 and November 2011. The design parameters of the five trial blasts were similar and are given in Table 1.

Each blast had 16 additional holes drilled to place Blast Movement Monitors (BMM®s) and coloured lengths of PVC pipes to measure the blast movement (Fig. 3) vectors. A total of 128 Blast Movement Monitors and 181 lengths of PVC pipes, were installed at varying depths and positions to understand the blast movement dynamics in the five blasts.

- Displacement of top red pipe was used to measure surface movement.
- A combination of the yellow pipe and the top BMM was used to measure movement in the top flitch.
- A combination of the green pipe and the bottom BMM was used to measure movement in the bottom flitch.
- The bottom red pipe was used to measure movement at the toe level.

Table 1 Parameters of three Trial Blasts

Blast Id	**AP1052_210**	**AP1052_211**	**AP1052_214**
Bench height (m)	8	8	8
Sub-drill (m)	1	1	1
Hole diameter (mm)	165	165	165
Total number of holes	462	537	517
Face confinement	choked	choked	choked
Burden & spacing (m)	3.5 & 4	3.5 & 4	3.5 & 4
Stemming (m)	3.5	3.3	3.3
Powder factor (kg/m³)	1.0	1.1	1.1
Blast Id	**AW1156_221**	**AW1156_222**	
Bench height (m)	8	8	
Sub-drill (m)	1.2	1.2	
Hole diameter (mm)	165	165	
Total number of holes	420	394	
Face confinement	choked	choked	
Burden & spacing (m)	4 & 4	4 & 4	
Stemming (m)	3.3	3.3	
Powder factor (kg/m³)	0.9	0.9	

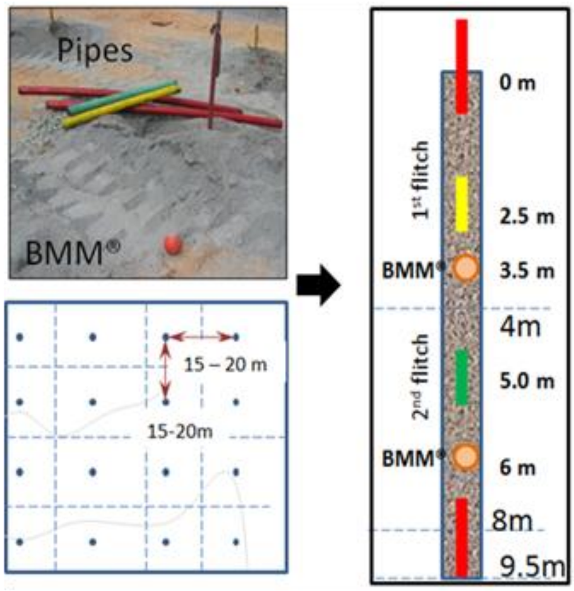

Fig. 3 Trial Blast Setup

2.1.1 Description of Blast Movement Monitor BMM®

The Blast Movement Monitor (BMM) is a system developed and patented by the JKMRC, University of Queensland and commercialised under licence by Blast Movement Technologies, Australia (La Rosa *et al.*, 2004). It consists of electronic transmitters placed within the blast volume prior to blasting which are then located after the blast with a special receiver. They provide accurate 3-dimensional movement vectors within hours of blasting and before excavation.

3 Blast Movement Measurements

A total of 115 BMM®s and 88 PVC pipes were recovered after the five trial blasts and used in the calculation of blast displacement vectors. The three dimensional vectors are resolved into horizontal and vertical components and key observations from this analysis are noted in the following sections. The trial blasts were also monitored with high speed videos to understand the effect of free faces and confinement on blast movement.

3.1 High Speed Video Observations

High speed video of the trial blasts highlights the following observations (Fig. 4).

- Rock mass moves preferentially towards the free face.
- At the back of the shot/power trough rock mass movement is quite different to that observed in the body of the blast.
- Along the high wall the movement is different because the explosive charging and timing was designed to minimize wall damage.
- Along the centreline, more cratering was observed due to higher confinement.

3.2 Horizontal Displacement

Horizontal displacement, pre-blast ore boundaries (top flitch) and timing contours (blue lines) for trial blast AP1052-211 are shown in Fig. 5.

The blast movement vectors from the blasts indicate the following:

- The direction of horizontal displacement is typically perpendicular to timing contours with the exception of areas influenced by the free face, edges, cratered holes and centreline.
- The horizontal displacement is greatest in the mid-bench region as shown in Fig. 6 (green pipe and bottom BMM). The magnitude of horizontal displacements range from 0.5 m to 20 m.
- Initiation point (IP) and centrelines in close proximity to grade boundaries are likely to cause increased mixing and dilution along the grade boundaries.
- The high variability in surface movement indicated by the top red pipe demonstrates the effect of the bench top as a second free face.
- The influence of semi-choked free face conditions is noticeable. Some large horizontal displacements of up to 20 m have been measured in this region.
- Limited horizontal displacement is observed on the high wall side of blasts as per designs to protect final walls.

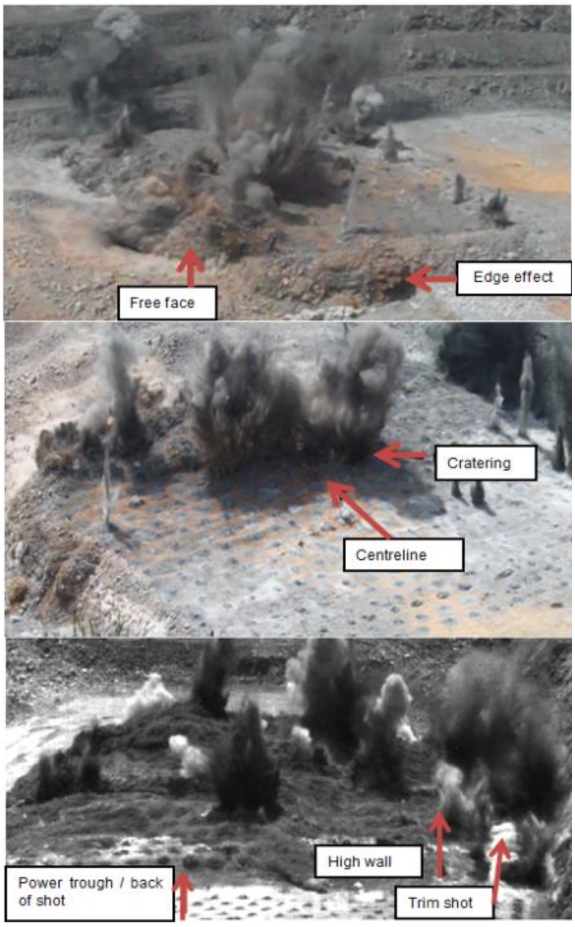

Fig. 4 High Speed Video Observations of Blast Movement

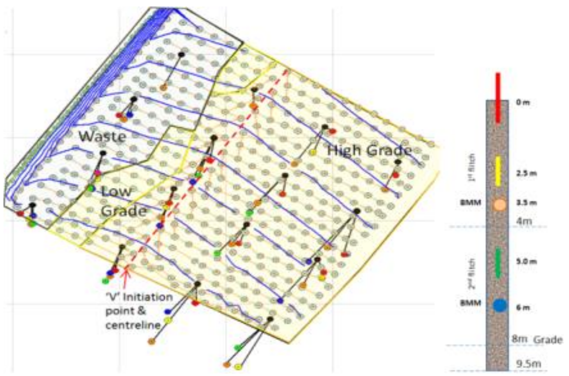

Fig. 5 AP1052-211 Measured Horizontal Blast Displacement Vectors

Fig. 6 shows the horizontal movement against the movement markers' initial installation depth for the five trial blasts.

A graph of most common horizontal displacements measured for the surface movement, top flitch and bottom flitch is given in Fig. 7. The horizontal movement vectors for the top flitch are a combination of the top BMMs and yellow PVC pipes. The bottom flitch is a combination of the bottom BMMs and green PVC pipes

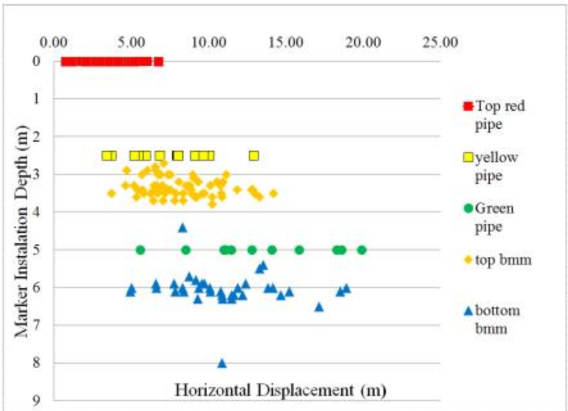

Fig. 6 Horizontal Movement as a Function of Installation Depth (m)

The most common horizontal movement vector for top flitch is 7 to 9 m and the bottom flitch is 11 to 13 m. On the surface the most common horizontal movement is between 3 to 5 m.

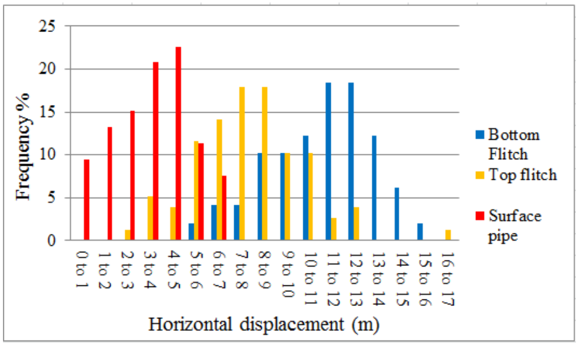

Fig. 7 Histogram of Horizontal Blast Displacement from All Five Trial Blasts

3.3 Vertical Displacement

Section view of the measured vertical displacement vectors for blast AP1052-211 is shown in Fig. 8. The magnitude of vertical displacements ranged from negative 1.2 m to positive 6.8 m. From the measured vertical displacement data and the analysis described in Fig. 8 and Fig. 9, the following can be concluded:

- The magnitude and direction of vertical displacement changes as the distance from the free face increases.
- Blast movement in the front row monitors experience more vertical displacement because of partial free face conditions.
- Surface of bench (top red pipe) moves mostly in the vertical direction.
- Movement at the back of the blast is different to that observed in the body of the blast.
- The depth of the power trough (Fig. 9) is measured to be approximately 5 m which is quite significant for 8 m bench and it acts as a partial free face for the blast behind.

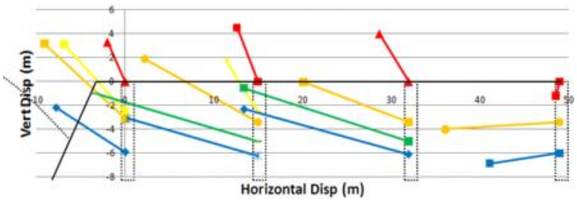

Fig. 8 Section View Blast Displacement Vectors

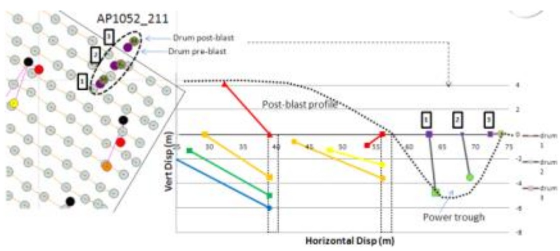

Fig. 9 Power trough Displacement Profile

3.4 Direction of Blast Movement

The general direction of blast movement vectors in all five trial blasts is perpendicular to the timing contours (Fig. 5). This result is similar to the observations made by Zhang (1994); Taylor *et al.* (1996); McKenzie *et al.* (1998); Adam and Thornton (2004) and Tordoir (2009).

In the stemming region, where the bench top acts as the free face, the rock mass in that region tends to move upwards (see Fig. 8). In practice the vector direction is not always perpendicular to the timing contour and a certain degree of variation from the theoretical value is expected due to edge effects and confinement conditions. A histogram of the variation from the theoretical 'as designed' timing contours for all monitors recovered after the blasts is shown in Fig. 10. The analysis indicates that:

- Blast movement is generally perpendicular to the timing contours with a degree of variation typically within ±20°.
- Direction of rock mass movement in the mid-

bench region is more consistent.

- Rock movement in the stemming region has more variation due to cratering and less than ideal confinement conditions.
- Rock movement near the edges, high walls, or near the centreline has greater degrees of variation due to inconsistent movement in these regions.

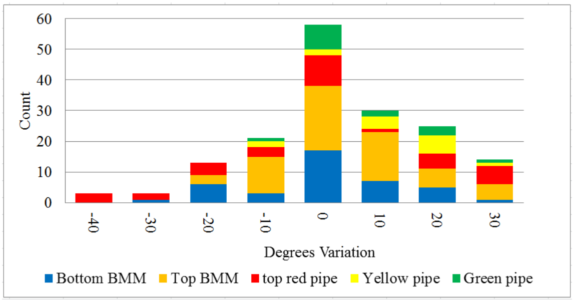

Fig. 10 Variation in Displacement Direction

4 Modeling and Analysis

4.1 Effect of Blast Movement on Grade Control

An important requirement for the financial success of an open pit metalliferous mining operation is accounting for the ore at the various stages throughout the mine life. The final and most accurate quantification of the localized spatial grade distribution prior to processing is generally achieved during the drilling of the blast pattern, as a result of assaying the drill cuttings and interpolating grade blocks between blast holes. During blasting, the rock mass moves and hence boundaries of ore polygons need to be adjusted to minimize dilution and ore losses.

The issue of ore losses and dilution due to blast-induced muck pile movement has previously been discussed by a number of authors including; Gilbride *et al.* (1995), Taylor *et al.* (1996, 2003), Harris *et al.* (1999, 2001), Firth *et al.* (2002) and Thornton *et al.* (2005, 2009).

4.2 Blast Movement Model '2DMove'

2DMove is an empirical displacement model developed at BRC (WH Bryan Mining and Geology Research Centre), at the University of Queensland, to predict grade displacement in open cut metalliferous blasts (Tordoir, 2009). The model estimates grade block displacements from known measured vectors. Blast movement measurements from the five trial blasts were used to calibrate the blast model and to quantify the impact on ore losses and dilution.

4.3 Estimating Ore Losses and Dilution

Prior to implementation of the blast movement study at Ahafo mine, the current practice was to mine to pre-blast grade boundaries (from blast hole drilling assays).

In this study, ore losses, dilution and misclassification are estimated in two steps:

1. Predict post blast ore boundaries from measured displacement vectors using the 2DMove.
2. Superimpose the post blast grade boundaries estimated from the 2DMove on the pre-blast ore boundaries to estimate ore loss, dilution and misclassification.

The grade and cost parameters shown in Table 2 are used to estimate the potential economic impact.

Table 2 Grade and Cost Parameters (based on 2010 production data)

Average Grade (g/t)	HG (g/t)	LG (g/t)
AP1052_210	4.04	0.96
AP1052_211	4.05	0.95
AP1052_214	4.24	0.94
Tonnes mined per flitch %	Top	Bottom
	0.55	0.45
Gold Price ($US/oz)	1,335	
Costs		
Mining ($US/t)	5.17	
Processing ($US/t)	19.42	
Plant Recovery %	85.80	

Fig. 11 illustrates the potential ore losses and dilution for the top flitch of trial blast AP 1052_210 when pre-blast ore polygons are not adjusted for blast movement. Blast movement for the top flitch is modelled using the displacement vectors from the top BMMs and yellow PVC pipes and the bottom flitch is modelled using the displacement vectors from the bottom BMMs and green PVC pipes. It is assumed that the 2DMove prediction of post blast ore boundaries is accurate and no over or under digging of ore takes place during excavation process.

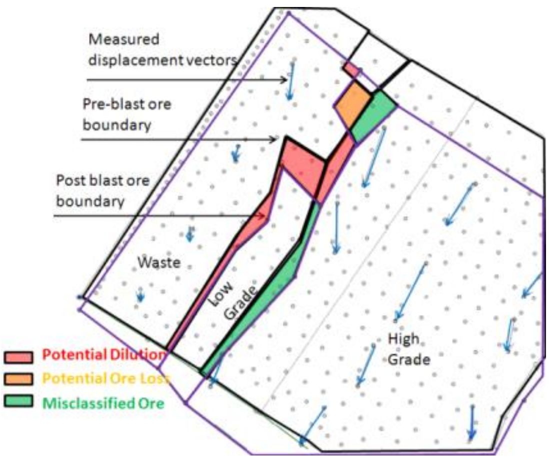

Fig. 11 2DMove Grade Displacement Model - AP1052_210 top flitch

Comparison of the pre-blast ore polygons versus blast movement adjusted ore polygons from 2DMove shows the potential ore losses, dilution and misclassified ore for the three Apensu trial blasts in Table 3. The grade and cost parameters provided are combined with the dilution, ore losses and misclassification estimates (Table 3) to estimate the overall economic impact for each blast. It can then be shown that the economic impact of ore losses and dilution, by not adjusting the ore polygons for blast movement, is estimated to be approximately US$0.5 ´ 10^6 and the opportunity cost due to misclassification is estimated to be approximately US2.5´ 10^6.

Table 3 Summary of Ore Losses, Dilution and Misclassified Ore

Trial Blast ID	Top Flitch			Bottom Flitch		
	Dilution %	Ore losses %	Misclassified %	Dilution %	Ore losses %	Misclassified %
AP1052_210	2.7	0.6	2.7	2.5	0	2.4
AP1052_211	4.2	0	4.6	4.6	0	8.2
AP1052_214	4.9	0.4	8.0	4.8	0	8.0

5 Alternative Strategies to Minimize Ore Losses and Dilution

Based on the understanding of blast movement dynamics from the trial blasts, alternative strategies were developed to reduce blast induced ore losses and dilution at Ahafo. These strategies included:

- Implement blast designs to promote consistent movement along the strike of the ore body and minimise inconsistent movement from edge effects, uneven free faces and cratering especially along the ore/waste boundaries.
- Adjusting the post blast ore boundaries to account for expected blast movement and to ensure that excavation follows the adjusted polygons.

5.1 Alternative Blast Designs

The utilisation of blast movement measurements to improve grade control, by altering blast design and initiation sequencing, has previously been discussed by a number of authors including Taylor *et al.* (1996), Harris *et al.* (2001) and Firth *et al.* (2002).
To minimise ore losses and dilution at Ahafo; blast design and implementation procedures were aimed at minimising edge effects (from power trough and free faces), uncontrolled movement (cratering) and detrimental blast movements (ore moving into waste or vice versa). Blast timing and initiation patterns were designed to promote consistent movement parallel to the strike of orebody.

Consistent and controlled blast movement along the ore strike is the most effective way of minimising ore losses and dilution and this was achieved by designing:

- A shallow 'V' initiation.
- Centreline away from ore/waste boundaries.

Edge effects result in inconsistent and uncontrollable blast movement and makes post blasts adjustments less effective. The edge effects were minimised by:

- Slowing down the timing in the back rows.
- Avoiding ore/waste boundaries in the power trough region in a blast.

Cratering and uncontrolled movement along ore/ waste boundaries increases ore losses and dilution. This was minimised by:

- Better QA/QC along the ore/waste boundaries.
- Better quality and increased stemming near ore / waste boundaries.
- Designing centreline away from ore/waste boundaries.

5.2 Post Blast Ore Boundary Adjustments

The method of using blast movement measurements to estimate average movement vectors for various regions of the blast has previously been discussed by Thornton *et al.* (2005). In this case, 'movement templates' were applied to pre-blast ore polygons to account for blast movement.

Blast movement monitoring results from the trial blasts showed that the direction and magnitude of movement in the body of the blast is consistent when the edge effects and inconsistent movements are kept to a minimum. Therefore the ore polygons can be adjusted for blast movement by applying the most common horizontal movement vectors. In this case the top flitch is adjusted by 8 m and bottom flitch by 12 m (see Fig. 6).

The direction of all ore polygon adjustments is made perpendicular to the timing contours because it is the most common direction measured during the trials (Fig. 10). The ore polygons adjustment method is shown in Fig. 12.

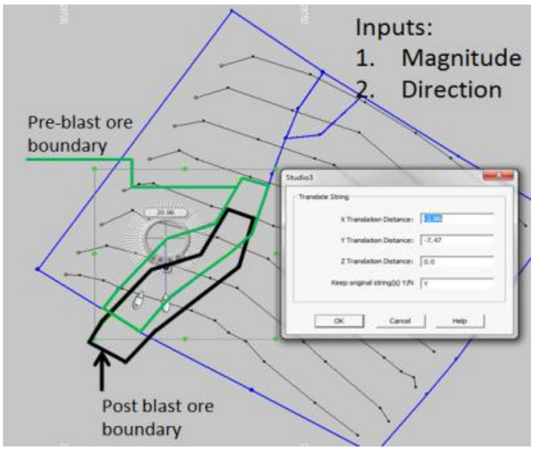

Fig. 12 Ore Polygons Adjustments Post Blast with Average Movement Vectors

For the three Apensu trial blasts, applying average movement adjustments to the ore polygons, to account for the expected blast movement, would have reduced the cost of ore losses and dilution by an estimated 33% (~ $US160,000) and opportunity costs from misclassification by an estimated 56% ($US1.5 million).

This method of applying average movements vectors to adjust post blast ore polygons is effective, timely efficient and alleviates the necessity to continually monitor future blasts.

6 Validation Trials

6.1 Setup

Two validation blasting trials were conducted to confirm the effectiveness of the above alternative strategies. The setup of the two validation blasts (i.e. AP-1028-211 and AP-1028-210) is shown in Fig. 13 and included the following:

- A total of 16 additional monitoring holes for each blast with two Blast Movement Monitors 'BMMs' and a 2 m long section of PVC pipe for each hole.
- Increased stemming heights of 0.5 m along the ore/waste boundaries.
- Flatter 'V' initiation timing used with 5 ms inter-hole and 67 ms inter-row (AP-1028-211) and 11 ms inter-hole and 81 ms inter-row (AP-1028-210).
- Initiation point (and hence centreline) located in centre of high grade block away from grade boundaries.
- The timing in the back few rows of each shot was slowed down using 119 ms inter-row delays.
- Greater focus and control on blast QA/QC was applied around low/medium and waste grade boundaries.

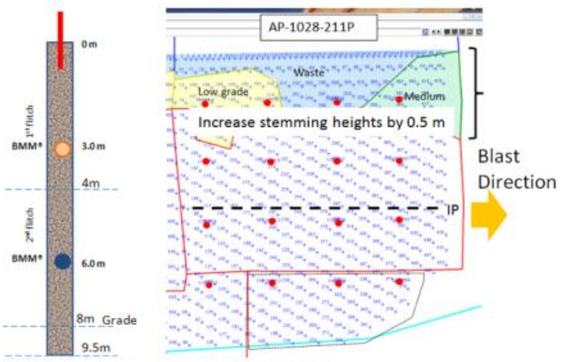

Fig. 13 Setup of Validation Trials

6.2 Results

6.2.1 Controlled Blast Movement

First validation trial blast (Fig. 14) had a partial free face (top 4 m of the bench) in the bottom right-hand corner resulting in edge effects during blasting. As the material in this section of the blast was all high grade ore, its effect on blast-induced ore losses and dilution was minimal. In this blast, 7 to 8 holes cratered out of about 450 blast holes. _Cratering along the ore/waste boundaries was observed even with the increased stemming (by 0.5 m). The reasons for this cratering may be due to:

- Inconsistent stemming due to manual shovelling of stemming material because of stemming loader breaking down during the trial.
- Stemming material being wetter than usual.
- The occurrence of wet holes particularly along the high wall side of the blast.

Fig. 15 Validation blast AP-1028-210

6.2.2 **Magnitude** and **Direction Blast Movement**

Horizontal displacement, pre-blast ore boundaries (bottom flitch) and timing contours (blue lines) for the first validation blast AP-1028-211 are shown in Fig. 5.

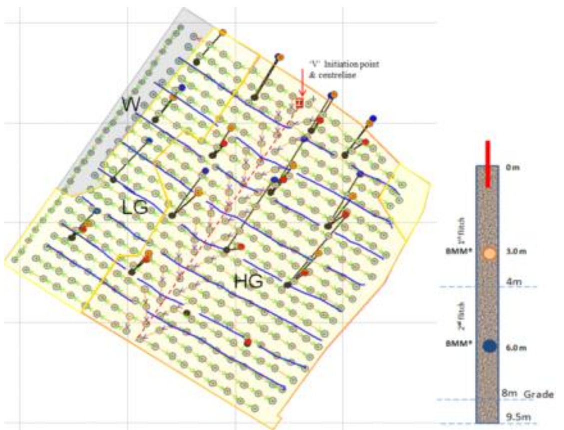

Fig. 16 AP-1028-211 Measured Horizontal Blast Displacement Vectors

Blast movement measurements from the validation blasts are comparable with the predictions from the 5 trial blasts suggesting that the predictions are accurate and reliable for the current conditions (Table 4 and Fig. 17).

Table 4 Summary of Measured Horizontal Movement Compared to Predicted

Average Horizontal Movement	Predicted from Trial Blasts (m)	Validation Blast 1 (m)	Validation Blast 2 (m)
Surface	4	4.0	3.5
Top flitch	8	9.0	7.3
Bottom flitch	12	12.9	11.1

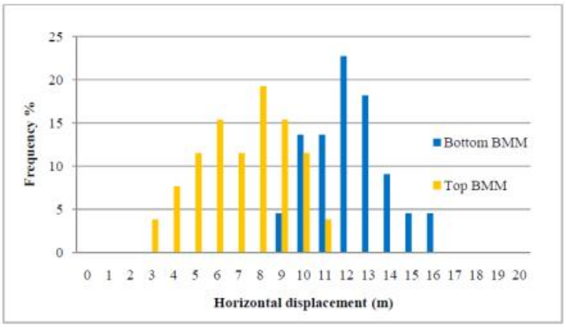

Fig. 17 Histogram of Horizontal Displacement for Validation Blasts

The validation blasts are split into two zones either side of the initiation point and the bearing perpendicular to the timing contours is calculated for both sides (Fig. 18) and compared to the average displacement directions measured from the BMMs. A summary of the results from this comparison is given in Table 5 and indicates little difference (less than 2º) between the measurements and predictions.

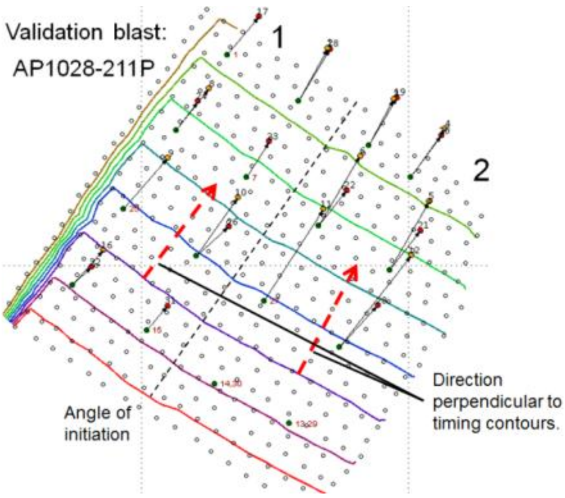

Fig. 18 Direction of Blast Displacement in Validation Blast AP1028-211

Table 5 Summary of Measured Direction of Blast Displacement Compared to Predicted

	AP-1028-211		AP-1028-210	
	Predicted Direction	Validation Results	Predicted direction	Validation Results
Zone 1	36^0	37^0	40^0	40^0
Zone 2	30^0	32^0	28^0	27^0

6.3 Comparison of Adjustment Method

The final validation is the comparison of ore polygons adjusted using the average movement vectors against the adjustment from the direct measurements, using the 2DMove blast movement model, for each blast. Fig. 19 shows the comparison for the top flitch of blast AP1028-211 and the bottom flitch of blast AP1028-210. The results show little difference (e.g. less than a bucket width) between the adjusted ore polygons using the measurements and by applying the average movement vectors.

Based on these results, it can be concluded that the recommended ore polygon adjustments using average movement can be a reliable method of accounting for blast movement for the current geological and blasting conditions at Ahafo Gold Mine.

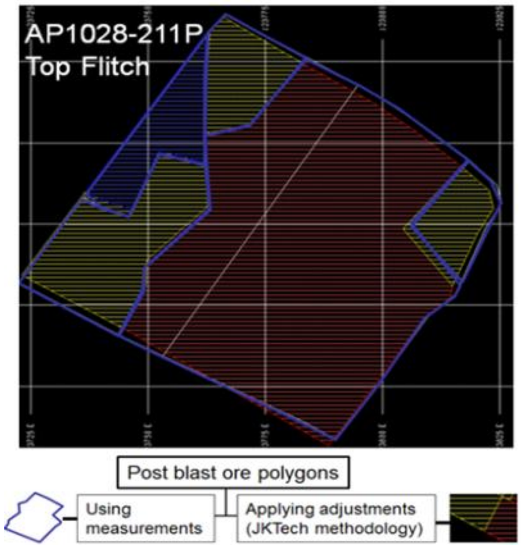

Fig. 19 Comparison of Ore Polygon Adjustments Applying Average Movements and Actual Measurements

7 Direct Benefits of Blast Movement Study

The Ahafo operations now adjust ore polygons to account for blast movements. The alternative strategies developed from this study have been incorporated in the standard site operating procedures.

Reconciliation data in Fig. 20 shows improved variation in Mine to Mill grade and reduction in diluted tonnes since after the implementation of the blast movement study in April 2011.

The graph captures variance for Mill tonnage, grade and ounces against what the Mine delivered. Percent difference = [(Mine – Mill)/Mine]´ x 100.

A number of improvements have been introduced since April and it is believed the biggest gains have been made from post-blast movement adjustments. Post-blast polygon adjustments have enabled ore to be recovered correctly and, ore losses and dilution to be minimized.

Blast hole sample size has been increased by 50% improving grade estimation and hence less variation in ounces recovered in the mill.

Increased supervision in the pit is also believed to have made a positive difference. There has been greater focus on heave mining techniques, ensuring grade blocks are captured correctly in dispatch and the correct sampling techniques are being followed.

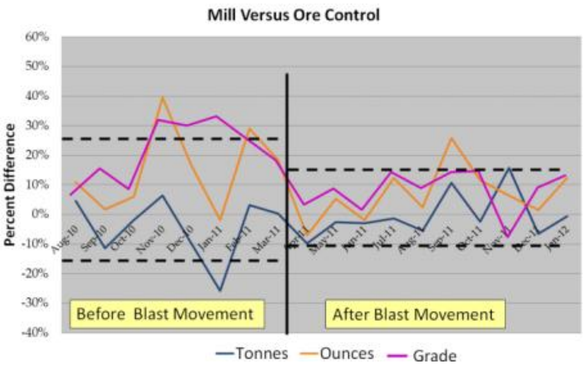

Fig. 20 Reconciliation – Reduction in Variation

8 Future Developments in Blast Movement Modeling

JKTech Pty Ltd. and the BRC (WH Bryan Mining and Geology Research Centre), at the University of Queensland, Australia continue to conduct research into blast movement and is currently developing a new 2–dimensional stochastic blast movement model. This model will enable distribution fitting to measured blast movement data, Monte Carlo simulations and risk optimization through establishment of confidence intervals around predicted grade boundary displacement.

A blast movement model currently in advanced stages of development at the BRC (WH Bryan Mining and Geology Research Centre) is MMS (3d Muck pile Modelling System). MMS (Fig. 18) is an empirically based three-dimensional model that takes into account full 3D particle interaction and allows for various blast energies and tie-up configurations to be simulated (Tordoir, 2009).

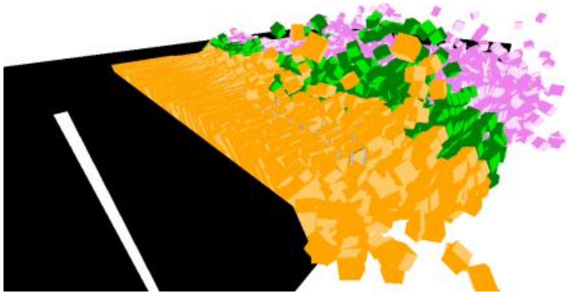

Fig. 21 Validation blast AP-1028-210

9 Conclusions

The main findings from the measurement and modelling of blast movement at Ahafo Gold Mine are:

- Uncontrollable and inconsistent blast movement take place due to uneven free faces, uneven drill patterns, poor stemming practices and excessive confinement along the center lines.
- In well controlled blasts, movement is consistent within the body of the blast except near the power trough, where the movement is different from the body of the blast.
- The general direction of blast movement is perpendicular to the timing contours with a degree of variation typically within ±20°.
- Mining ore with pre-blast boundaries can have significant adverse economic impact as direct cost due to ore losses and dilution and as indirect opportunity cost due to misclassification of low grade ore as high grade ore.

The validation trial results demonstrated that ore losses and dilution can be reduced by:

- Implementing blast designs to promote movement along the strike of the ore body and to minimize inconsistent movements along the ore/waste boundaries
- Adjusting the ore polygons for blast movement using the average movement vectors measured.

References

Adam, M. and Thornton, D. (2004), "A New Technology for Measuring Blast Movement", Innovative Mineral Developments Symposium, *Australasian Institute of Mining and Metallurgy*, Shore School, North Sydney, NSW, Australia, pp. 87 - 96.

Firth, I. R., Mousset-Jones, P. and Daemen, J. (2002), "Blast Movement Measurement for grade Control", *Proceedings of the 28th Annual*

Conference on Explosives and Blasting Technique. Annual Conference on Explosives and Blasting Technique, International Society of Explosives Engineers, Las Vegas, Nevada, USA, pp. 55 - 68.

Gilbride, L, Taylor, S and Zhang, S. (1995), "*Blast-Induced Rock Movement Modelling for Nevada Gold Mines*", in Mineral Resources Engineering, 4(2), pp. 175 - 193.

Harris, G. W., Mousset-Jones, P. and Daemen, J., (1999), "Measurement of Blast-Induced Rock Movement in Surface Mines by Application of Magnetic Geophysics", *Transactions of the Institutions of Mining and Metallurgy, Mining Technology*, 108, pp. A172 - A180.

Harris, G. W., Mousset-Jones, P. and Daemen, J. (2001), "Blast movement measurement to control dilution in surface mines", *CIM Bulletin*, 94 (1047), pp. 52 - 55.

La Rosa, D., Thornton, D. and Wortley, M. (2004), "*Blast movement monitor and method for determining the movement of a blast*". Patent number 7367269, Brisbane, Australia.

McKenzie, C. K., Geddes, P., Grohs, K. and Morrish, M. (1998), "Blasting Trials to Control and Monitor Displacement of Narrow Vein Gold Ore", *Proceedings of The Twenty-Fourth Annual Conference on Explosives and Blasting Technique. Annual Conference on Explosives and Blasting Technique*. International Society of Explosives Engineers, New Orleans, Louisiana, USA, pp. 145 - 164.

Taylor, S. L., Gilbride, L. J., Daemen, J. J. K. and Mousset-Jones, P. (1996), "The Impact of Blast Induced Movement on Grade Dilution in Nevada's Precious Metal Mines", *Proceedings of the Fifth International Symposium on Rock Fragmentation by Blasting – Fragblast-5*, (I B. Mohanty, ed.), A. A. Balkema, Montreal, Canada, pp. 407 - 413.

Taylor, D. L. and Firth, I. R. (2003), "Utilization of Blast Movement Measurements in Grade Control", in *Application of Computers and Operations Research in the Minerals Industry* (Southern African Institute of Mining and Metallurgy: Marshalltown), pp. 243-247.

Thornton, D., Sprott, D. and Brunton, I. (2005), "Measuring Blast Movement to Reduce Ore Loss and Dilution", *Proceedings of the Thirty-First Annual Conference on Explosives and Blasting Technique*. International Society of Explosives Engineers, Orlando, FL, USA, pp. 189 - 200.

Thornton, D. (2009), "The Implications of Blast-Induced Movement to Grade Control", in Seventh *International Mining Geology Conference*, Perth WA, Australia, pp. 287 – 300.

Tordoir, A. E. (2009), "*2DMove Blast Displacement Model – Preliminary User's Manual*", University of Queensland, Brisbane, Australia, pp. 1 – 4

Tordoir, A. E. (2009), "*A Study of Blast Induced Rock Mass Displacement through Physical Measurements and Rigid Body Dynamics Simulations*", PhD Thesis, University of Queensland, Brisbane, Australia, pp. 118 – 130

Zhang, S. (1994), "*Rock Movement Due to Blasting and Its Impact on Ore Grade Control in Nevada Open Pit Gold Mines*", M Eng Sc Thesis, University of Nevada, Reno, 155 pp.

Authors

Eric Engmann is the Chief Mine Geologist for Newmont Ghana Gold Ltd. He holds a master's degree in Mineral Exploration with 16 years industry experience in both exploration & mining geology. He is a member of AusIMM.

Seth Ako: Master Black Belt – Lean Six Sigma Continuous Improvement, Newmont Ghana Gold Ltd. Seth completed Geological Engineering Diploma at University of Mines & Technology, Tarkwa, Ghana in 1997 and has combined 15 years of experience in mineral exploration, mine geology and mine operations. He is a member of SME and AusIMM. Seth is currently on a post graduate program in Management Studies with Paris Graduate School of Management

Wayne Rogers; Senior Mining Engineer, JKTech Pty Ltd, Brisbane, Australia. Completed his Mining Engineering degree at the University of Western Australia in 2004 and joined JKTech in 2010. Wayne is currently completing his Master's thesis in blast movement modelling.