Rock Engineering Department

Project Report

Characterizing rock mass behavior in terms of fracture formation using micro seismic monitoring: Preliminary project report

SANIRE Symposium 2013

Author: Christiaan F. van Rooyen

Date: September 2013

Table of contents

List of figures

1 Introduction

This document has been prepared for the SANIRE Symposium, 7-8 November 2013. The purpose of this document is to introduce the reader to the history leading up to, methodology employed and current project status. The project itself is on-going and updates will be made available as the project progresses.

This project was initiated in to gain insight into the behaviour of the Anorthositic rock type which comprises the hangingwall of the Merensky reef horizon. An opportunity in the form of an abnormally active area at the Lonmin Karee 4 Belt operations to study the hangingwall behaviour presented itself.

2 Background

It is a well-established fact that, on the Merensky reef horizon, the Anorthositic hangingwall is often problematic. The primary difficulty encountered is that the Anorthositic hangingwall tends to behave as a highly stressed rock mass in an apparently low stress environment.

As stated above a specific area at the Lonmin Karee 4 Belt operations was found to be significantly more active in terms of fracturing and falls of ground related to the Anorthositic hangingwall. The active area is currently limited to 4 raise lines in the western portion of 8 level which is approximately 250mbs. The raise lines are 8mW26, 27, 28 and more recently 29.

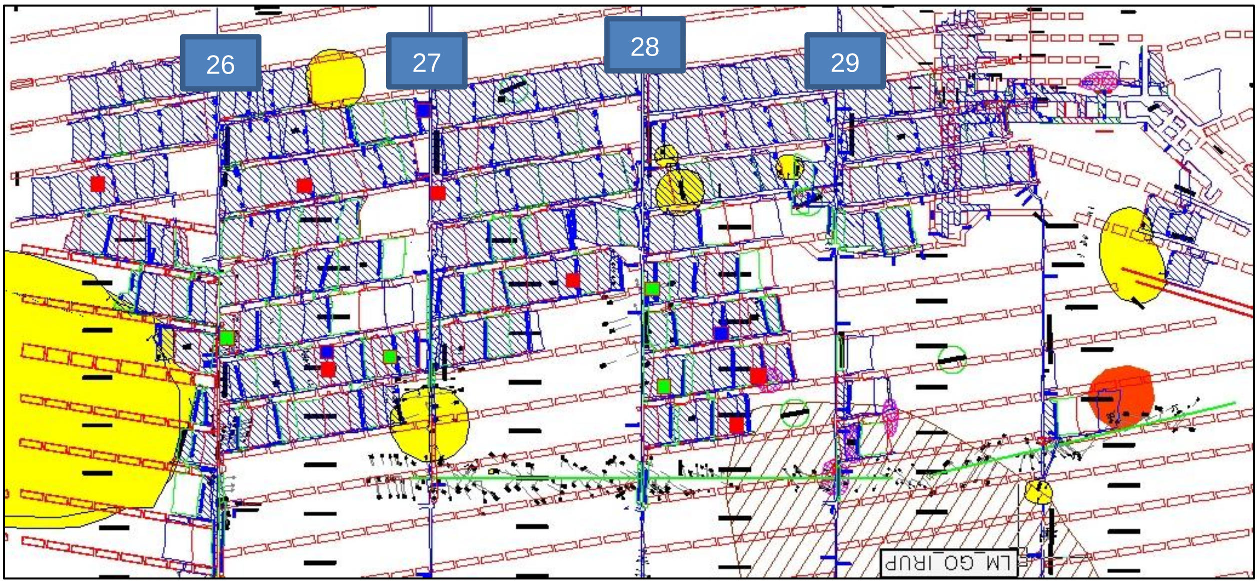

Figure 1: Plan of the area (North is towards the top)

The 8 level west stoping has experienced a bout of adverse ground conditions during the last two years. Since March 2012 up to the current date a total of 11 falls of ground have been recorded of which 6 were of sufficient dimension to be regarded as dangerous occurrences. A total of 3 panel collapses were recorded and 3 of the recorded falls resulted in injuries. 3 panels have also been abandoned due to tell-tale signs of the onset of failure being present.

All of the recorded falls of ground are related to fracturing in the Anorthositic hangingwall. In most cases evidence of stress related damage was present. The larger falls have caused extensive damage to the installed support.

The area is reasonably un-jointed but minor potholes and reef rolls are present. A large iron rich ultramafic pegmatoidal body is present towards the Southeast.

Figure 1 above indicates the area and extent of falls of ground. Red squares indicates falls regarded as dangerous occurrences, blue squares indicate falls greater than the support spacing and green squares indicate falls smaller than the support spacing.

Examining the positions of the major falls of ground a clear trend can be seen striking approximately southeast. It is the orientation of the major falls of ground on plan that gave rise to the suspicion that a zone of “something” exists.

On a shaft scale large falls of ground have been recorded following the same trend. Figure 2 below indicates the falls of ground along with major faults.

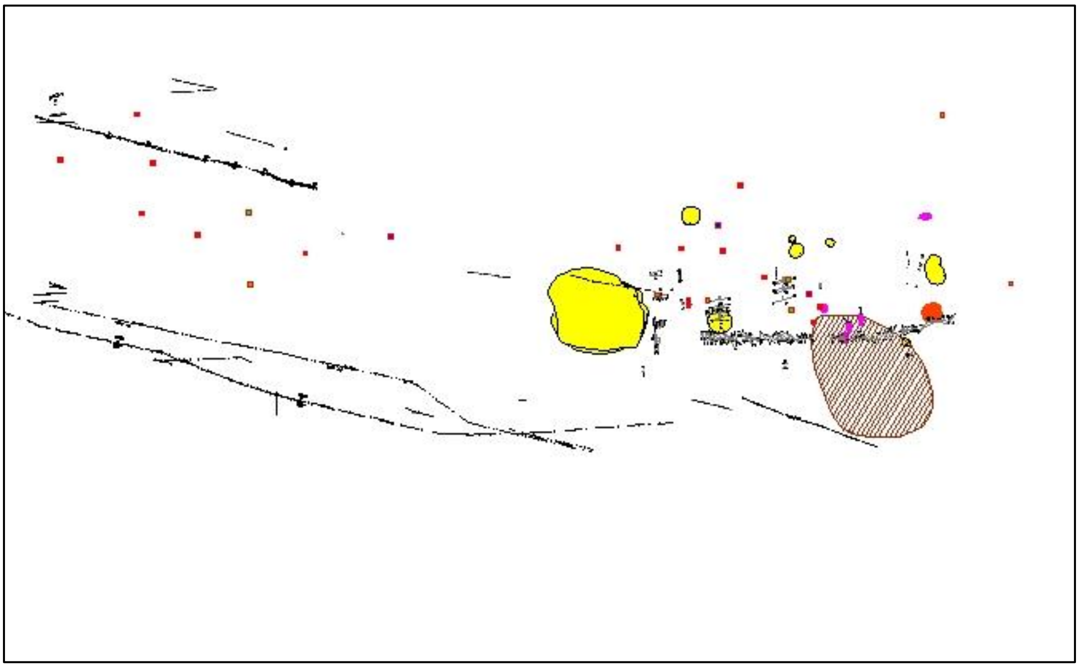

Figure 2: Fall of ground trend (North on top)

From the plan it appears that the major falls of ground tend to occur along a zone which follows the fault system shown to the south on the plan with an increase in occurrence close to the IRUP body towards the southeast.

As stated previously the falls that occurred in the 8 level west area had some evidence of stress related damage. The following series of photographs illustrate the typical failures encountered.

Figure 3: 8mW28W2 Note the smooth, flat fracture plane

Figure 4: 8mW28 W2

Figure 5: View along the ASG

The following series of photographs were taken approximately one week prior to the collapse shown in figure 5 above.

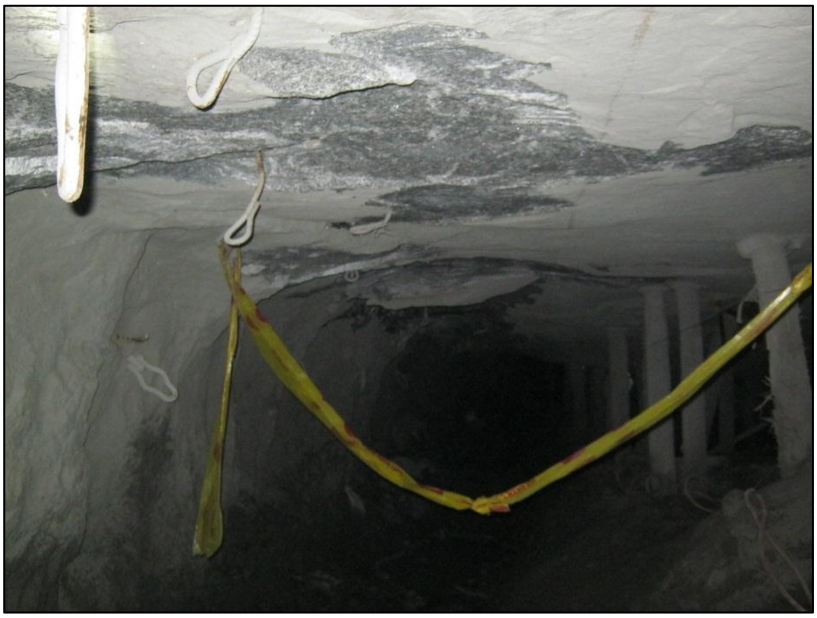

Figure 6: View along the ASG

Figure 7: View along the ASG

Figure 8: Scaling at the pillar/ASG interface

Figure 9: Open fracture in the ASG hangingwall

The following photograph was taken recently. Note the clearly defined fracture plane originating from the stope face.

Figure 10: Fracture plane originating from stope face

Given all the evidence a hypothesis was formulated that the driving force responsible for these failures may be stress related and specifically; some form of locked up stress, possible of tectonic origin.

A comprehensive project report commonly known as the Platmine report was published in 2005 regarding the behaviour of Anorthositic rocks in platinum mines. A review of this document gave insight into some of the mechanics involved. This is described in detail in the following sub-section.

2.1 Platmine project – Understanding the mechanical properties of the Anorthosite suite of rocks

Full document reference: *Understanding the mechanical properties of the anorthosite suite of rocks B.P.Watson, M.K.C. Roberts, A.J. Jager, K Naidoo, R. Handley, D.P. Roberts, E.J. Sellers(CSIR Mining Technology) Y. Kanagalingam (University of Witwatersrand)*

This document has been studied intensively in an attempt to understand the mechanisms that drive the instabilities encountered in the 8mW area. The following is quoted regarding failure mechanisms:

"Three credible failure mechanisms emerged from the investigations. These are:

- ***the extension strain criterion proposed by Stacey (1981);***
- ***the ability of massive, unjointed rock masses to carry high tectonic stress as suggested by Martin (1990); and***
- ***high stresses adjacent to and within geological structures such as potholes, dykes and faults."***

Evidence of all three situations described above was found during site inspections following large collapses. Section 2.3.1.4 of the Platmine report is quoted below:

"2.3.1.4 Implications of the pothole measurements

The results of the investigations show that the stress measurements were reliable. The study indicated an anomalously high stress condition in the anorthosite section of the pothole, which was sufficient to cause the observed fracturing under normal Mohr-Coulomb conditions. The measurements also suggest that high tectonic stresses were associated with the pothole structure."

And also section 2.3.2.4:

"2.3.2.4 Conclusions

The limited stress measurement database suggested that the anorthosites may carry higher tectonic stresses than the norites and pyroxenites. However, the high stresses measured in the pothole and the fracturing in anorthosites at very shallow depth is not explained by the database."

It appears from the Platmine report that the suspicion of locked up tectonic stress, or at least, a significantly higher than expected stress condition in the Anorthositic rock is valid. It was felt;

however, that site specific monitoring will be able to give a more detailed insight into the mechanisms.

3 Monitoring methodology

A method to monitor fracture formation and propagation is through micro seismic monitoring. In principal, each fracture that is formed generates a pulse of energy into the rock mass which can be recorded as a seismic wave if the instrumentation used is sufficiently sensitive. It was originally envisioned that from the recorded seismic waves the following primary data sets can be determined:

i. Amount of events (Fracture formed, propagated) within a certain amount of time.
ii. Magnitude of each event. (Amount of energy released).
iii. Frequency of events. (Fractures formed, propagated per time unit).

From the interpretation of the actual recorded data it was found that this original approach as stated above would not yield the insight expected. During the monitoring period three incidents occurred where stope faces suddenly started to experience extensive face area fracturing. Unfortunately the data at one of these sites was not recorded. Two of these work places have since been abandoned to the excessive fracturing. The micro seismic instruments were installed in these panels. For the purpose of this report two incidents will be scrutinised. As a third case, a monitoring site was established at the same depth and reef horizon east of the primary monitoring site. This area has never experienced any instability and will be used as the normal case.

3.1 Monitoring equipment

An instrument called a FOGWarn is available from the CSIR. This device was originally designed to provide an early warning of immanent collapse in coal mines using long wall techniques (GOAF). For this reason the instrument is extremely sensitive and is capable to record events to a magnitude of (-3.) on the Richter scale.

Each instrument has a limited detection range, typically in the order of a 50.0m radius. This will assist in ensuring that only one face is monitored by each instrument.

These instruments are easy to install: The geophone is attached to the rock face by means of a strong adhesive. No drilling is required and the system is relatively cheap.

The system is limited, however, as no insight is given into the actual locations of recorded events. It was felt, however, that the data that will be recorded will be sufficient to gain an initial understanding of the mechanisms involved.

Figure 11: Installed FOGWarn unit

4 Monitoring Results

4.1 Closure monitoring

Following the initial instabilities 3 continuous closure loggers were installed in the 26, 27 and 28 lines, one per line. The graph below indicates the closure measurements over a period of 2 months while the panels where the loggers were installed were actively mining.

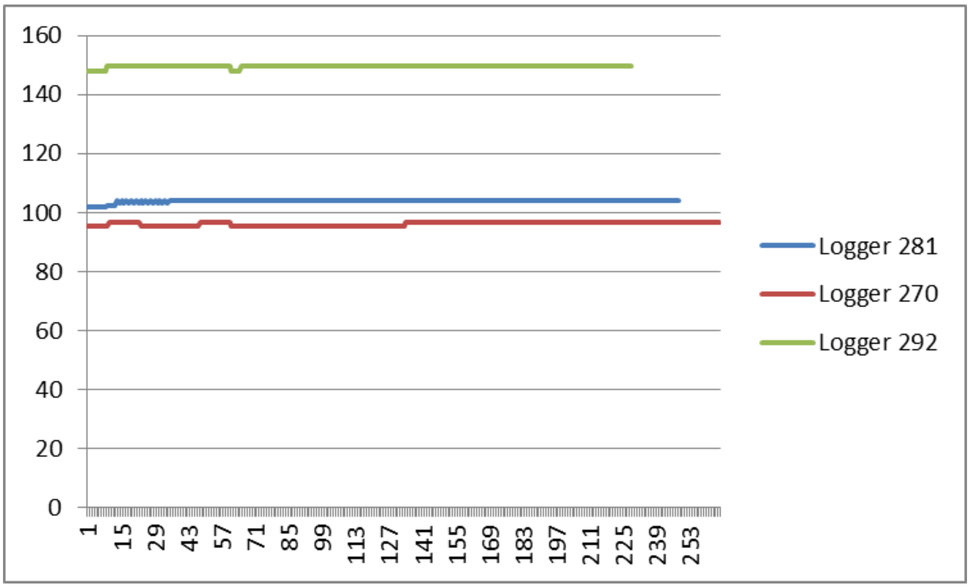

Figure 12: Closure data

A maximum closure of 1.5mm was recorded. It can therefore be concluded that the environment can be described as rigid with minimal, if not neglible, closure.

4.2 Case study timeline

In order to create context a timeline for each of the two cases that will be dealt with are given.

Panel	First investigation	Stoppage	Instrument installed	Analysis interval
8mW29 W5	25/07/2013	1/08/2013	1/08/2013	From installation date for 2 weeks
8mW29 W4	11/09/2013	Still mining	5/09/2013	From installation to 16/09/2013

Analyses on the entire data sets are on-going.

Separate analysis for each working place are presented in the section following. Each analysis consists of the following:

1. Peak particle velocity plot for the analysis interval. All data points are included.
2. Peak particle velocity plot for all blasts and 4 hours post blast.
3. Peak particle velocity plot for unusual occurrences.

It should be noted that for the available timeframe for submission of this document only initial basic analysis will be presented.

4.3 8mW29 W5 Analysis

Although the panel was stopped development of the ASG continued. For this reason blast intervals were recorded regularly.

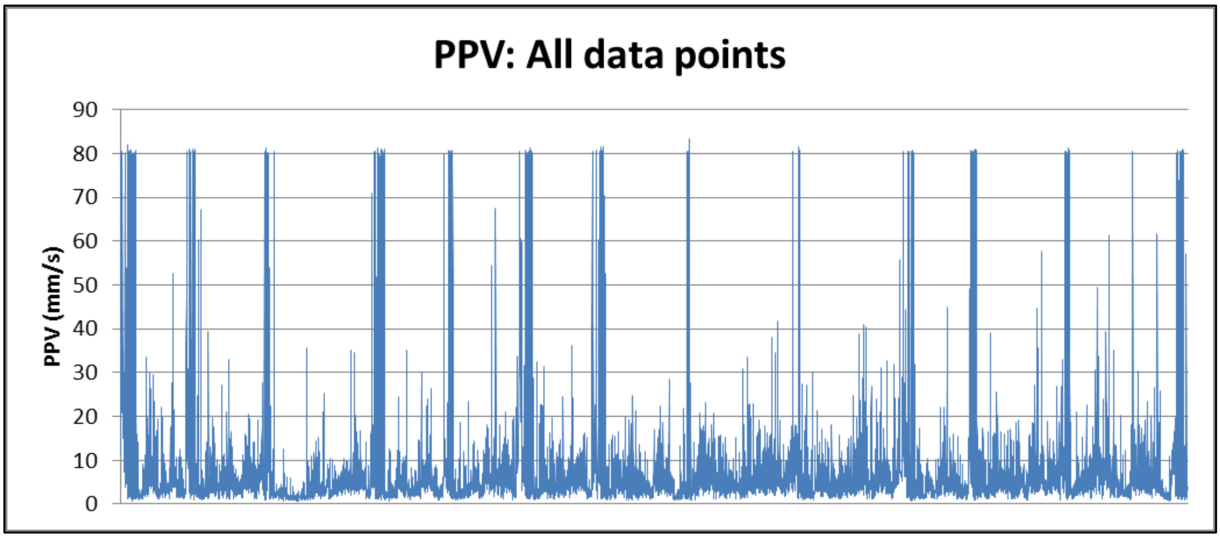

Figure 13: 8mW29W5 All data plot

As can be noted a PPV of above 70 mm/s is associated with the blast. To ensure that only hangingwall "noise" is reflected the blast itself has been filtered out in the next graph. The time period between 13:30 and 19:12 is examined. The shaft blast time is 14:00. Therefore, it can be stated with reasonable certainty that applying the time constraints as stated will primarily reflect hangingwall "noise".

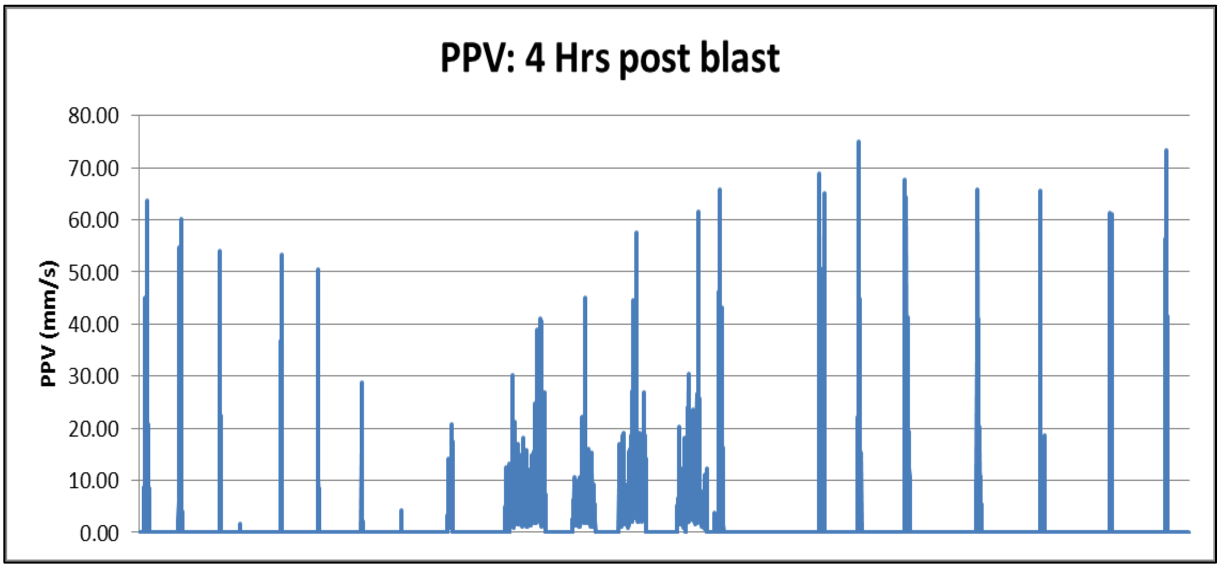

Figure 14: 8mW29 W5 Post blast plot

The plot for "unusual" events is defined as those events occurring during shift hours with a reasonably high PPV. As can be seen from the all-inclusive plot work "noises" do not typically exceed 40 mm/s. For this reason "unusual" occurrences are marked as an event with a PPV greater than 40mm/s which occur between 00:00 and 13:00 the next day. It should be noted as a reference frame that at 40 mm/s half of the intensity of the blast is reached. Typically, it is not expected that any shift work causes a disturbance of such magnitude. The sensors are installed in excess of 20.0m from any working face and therefore it is unlikely that any high intensity disturbances are created close to the sensors which may skew the data. To ensure that no late blasts are included all data points with a PPV of 80 mm/s or more has also been excluded.

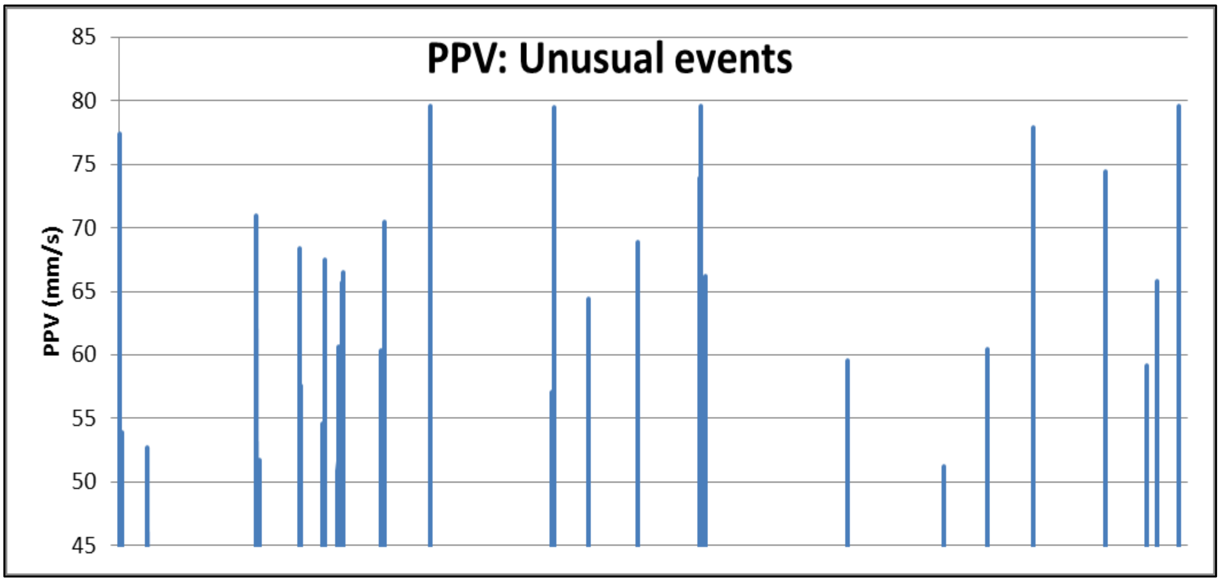

Figure 15: 8mW29W5: Unusual events

4.4 8mW29 W4 Analysis

The next two sections will only contain the graphs since the assumptions have already been discussed above.

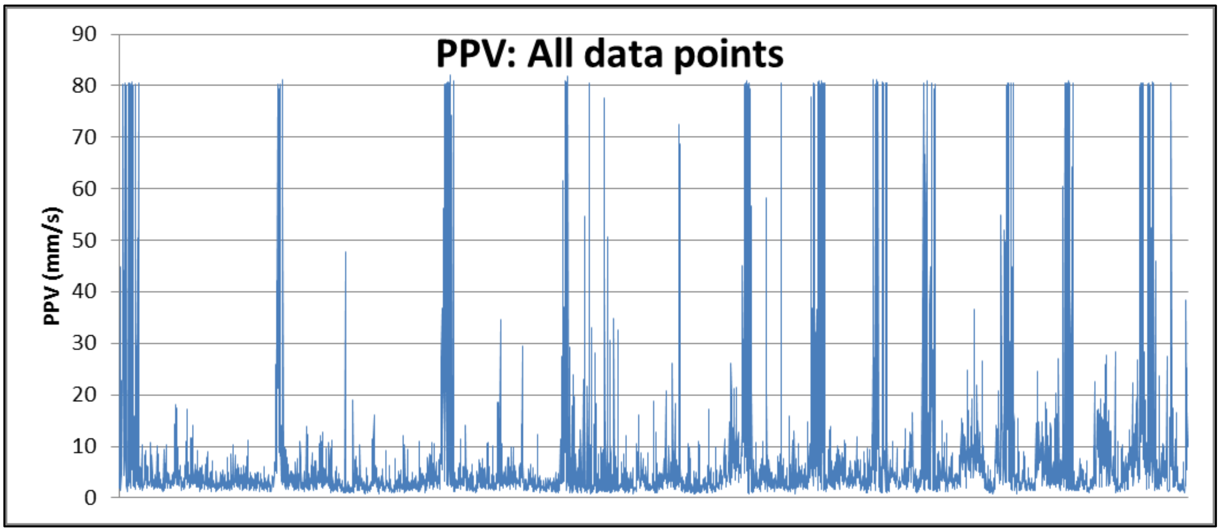

Figure 16: 8mW29W4 All data points

The red line on the following two graphs indicates the investigation day.

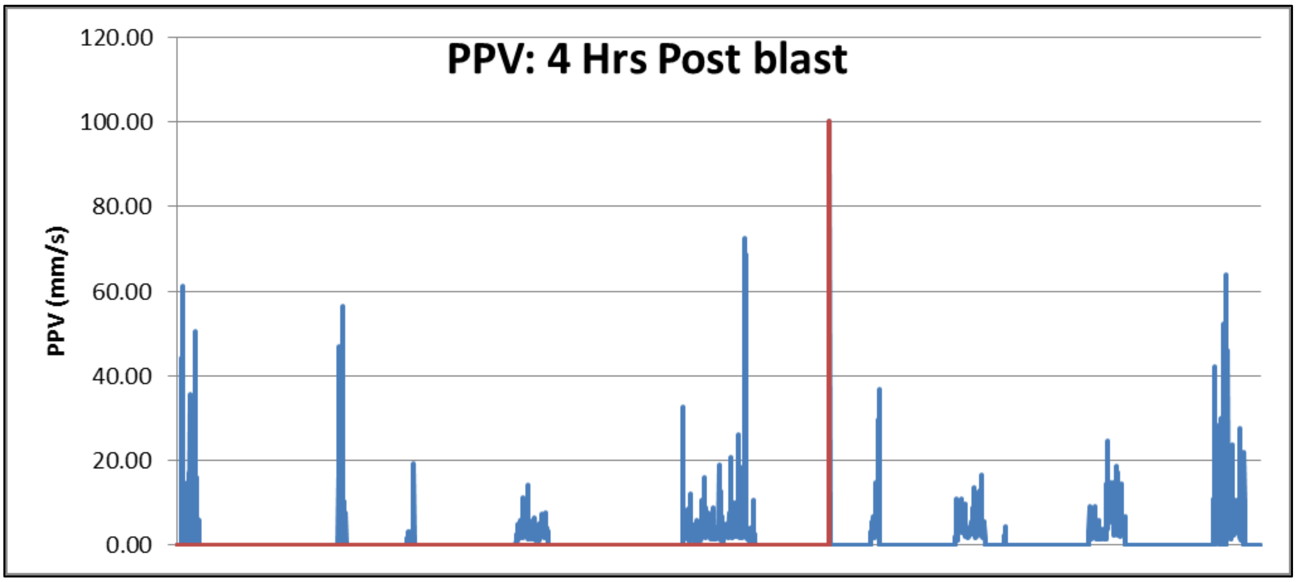

Figure 17: 8mW29W4 4 Hours post blast

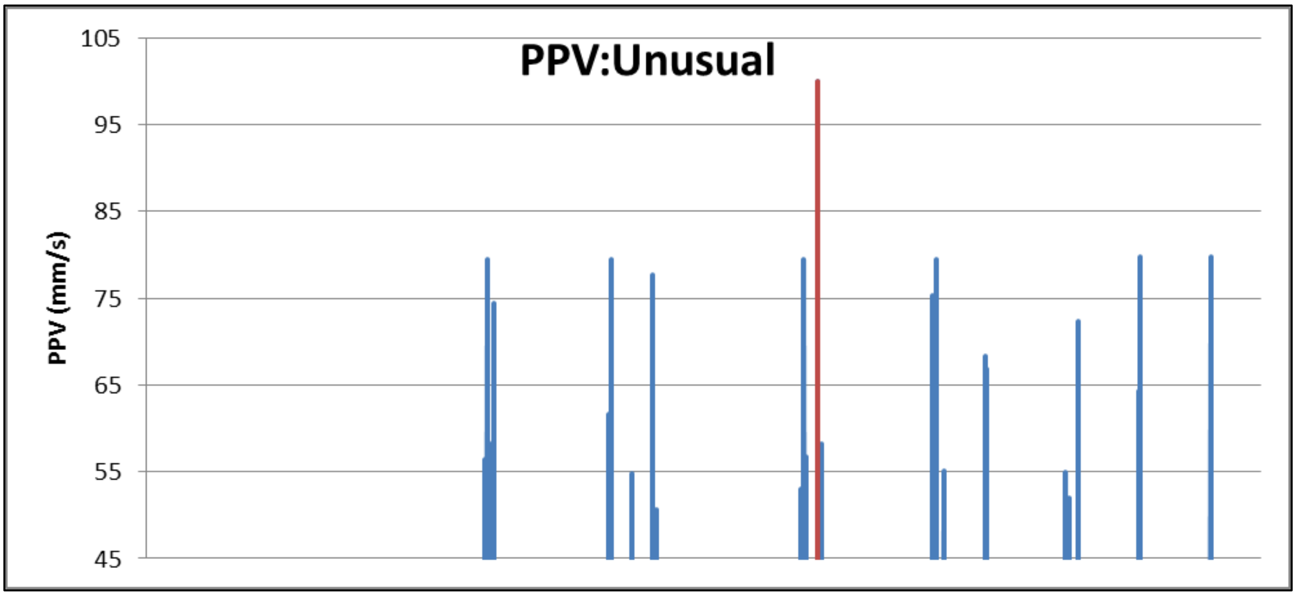

Figure 18: 8mW29W4 Unusual plot

4.5 8mE22 E2 W1 Analysis

This site was monitored for a month. All data will be considered. As stated this area has never experienced any related adversities and was selected for this reason.

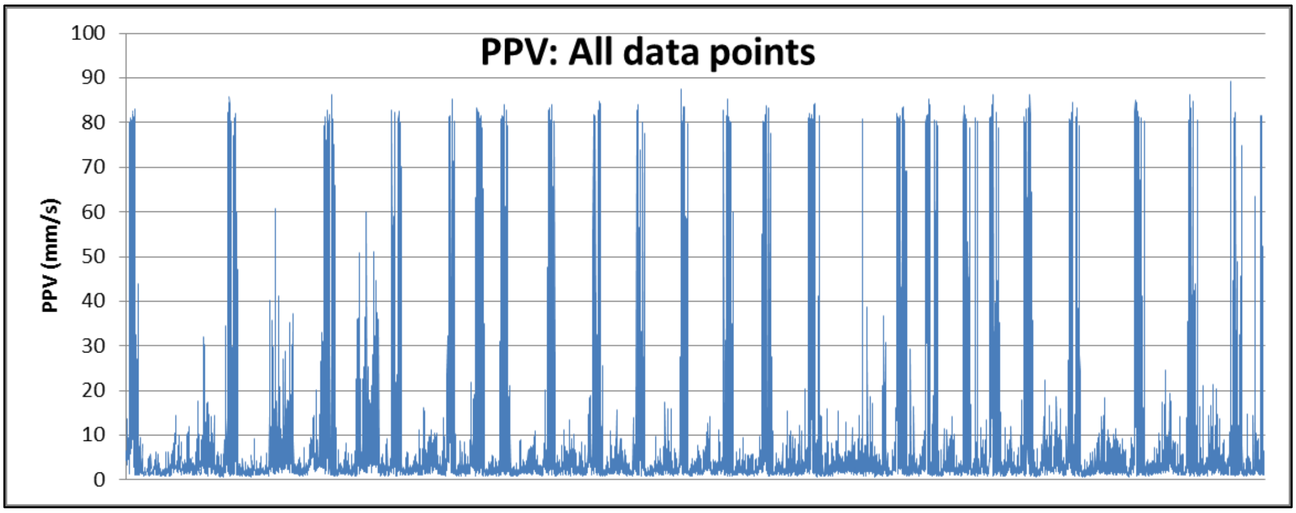

Figure 19: 8mE22E2 All data points

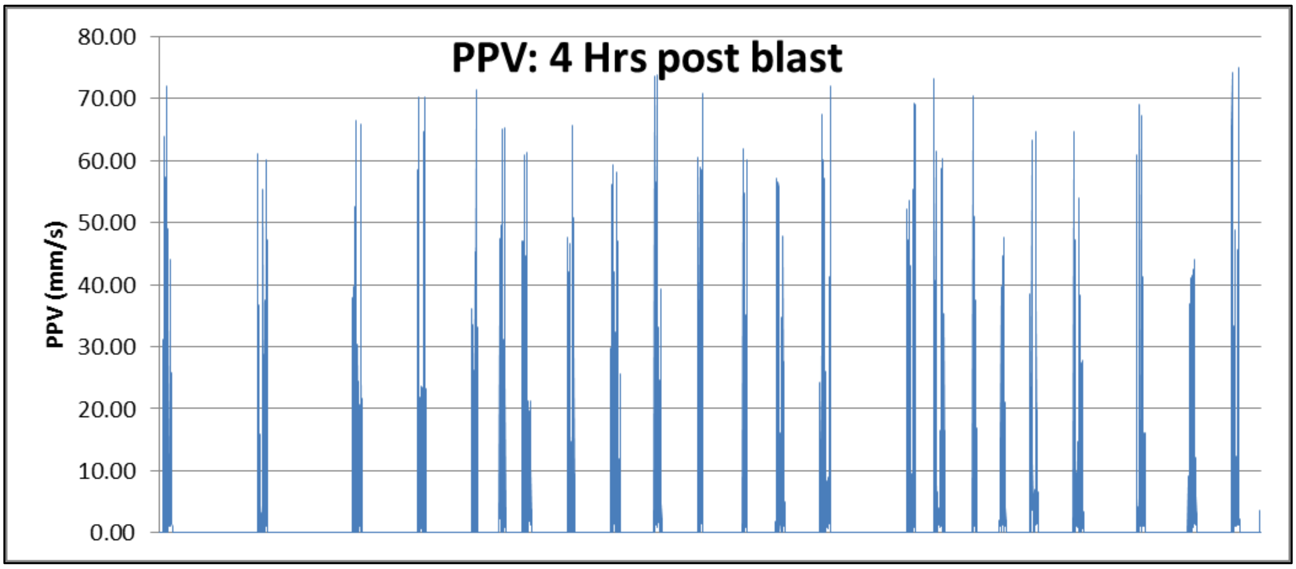

Figure 20: 8mE22E2 4 hours post blast

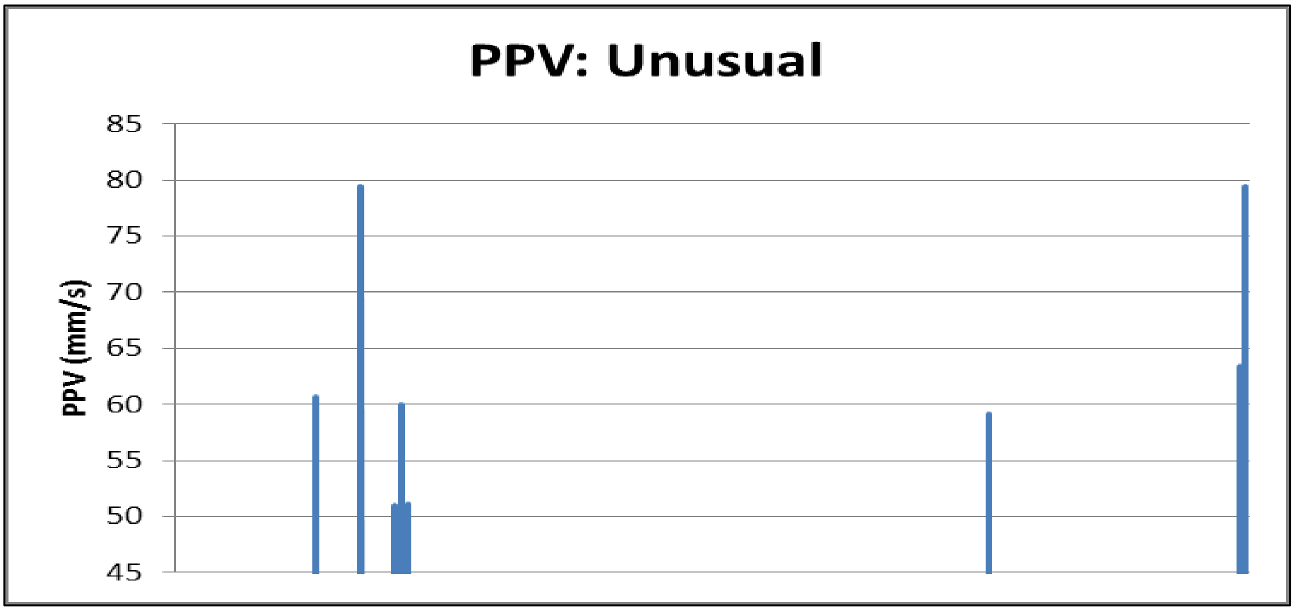

Figure 21: 8mE22E2 Unusual plot

5 Comparison between the different graphs

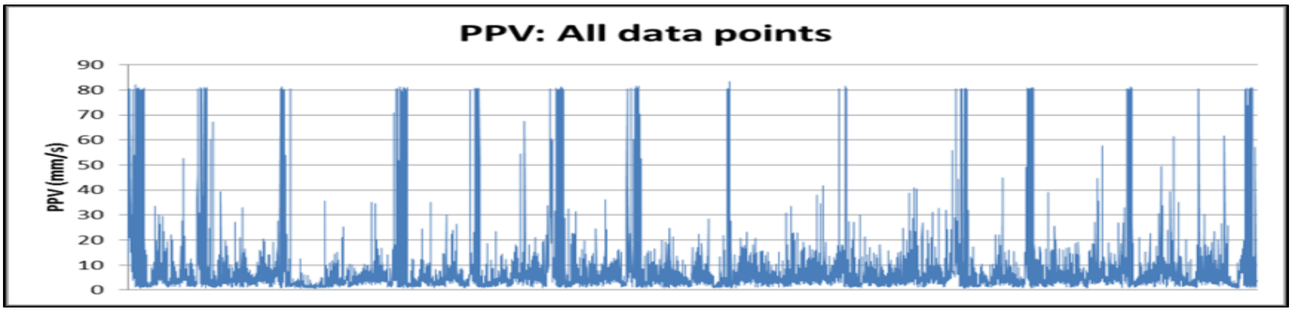

Figure 22: 8mW29 W5 All data

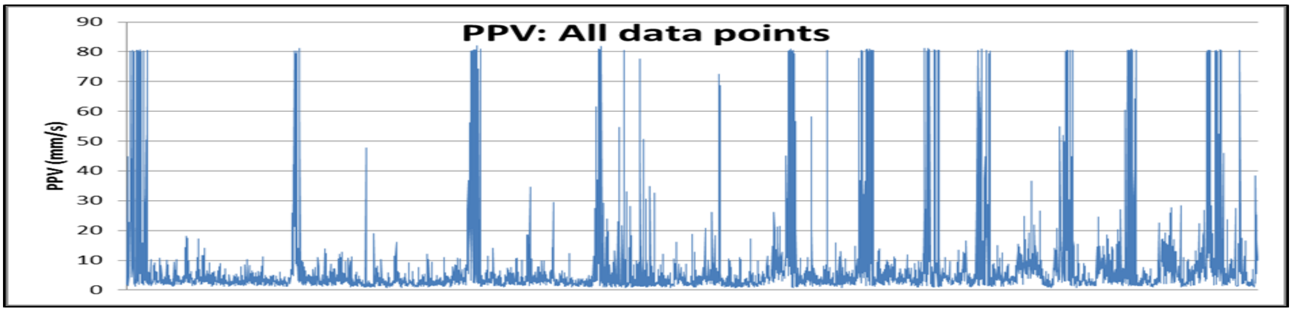

Figure 23: 8mW29 W4 All data

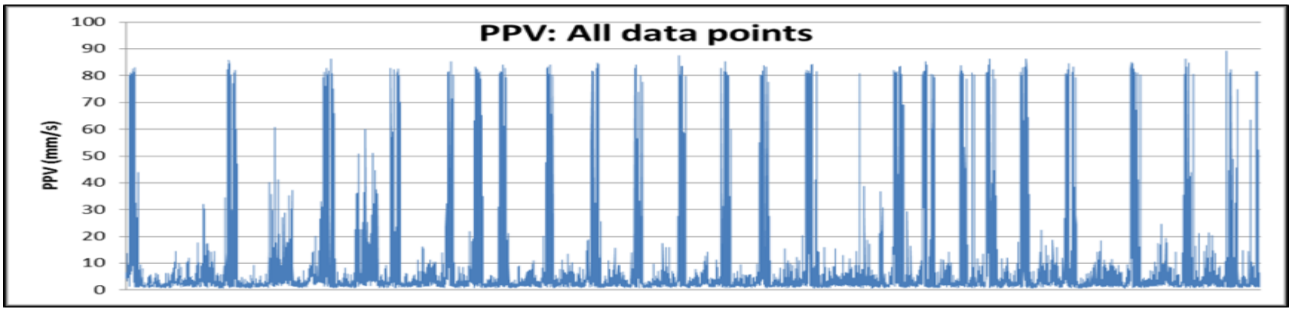

Figure 24: 8mE22 All data

At first glans the overall data sets appear to be very similar. Closer inspection, however, reveals some interesting discrepancies:

1. The peak particle velocities achieved during blasts are consistently slightly higher at the control site when compared to the primary sites.
2. Lower velocity activity densities are apparent in both the control site and the 29W4 site, where mining continued, as compared to the 29W5 site.

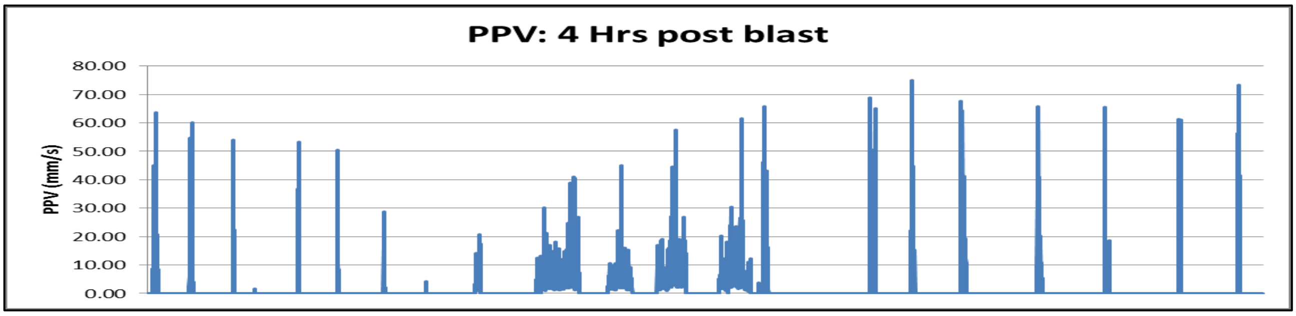

Figure 25: 8mW29 W5 4 hours post blast

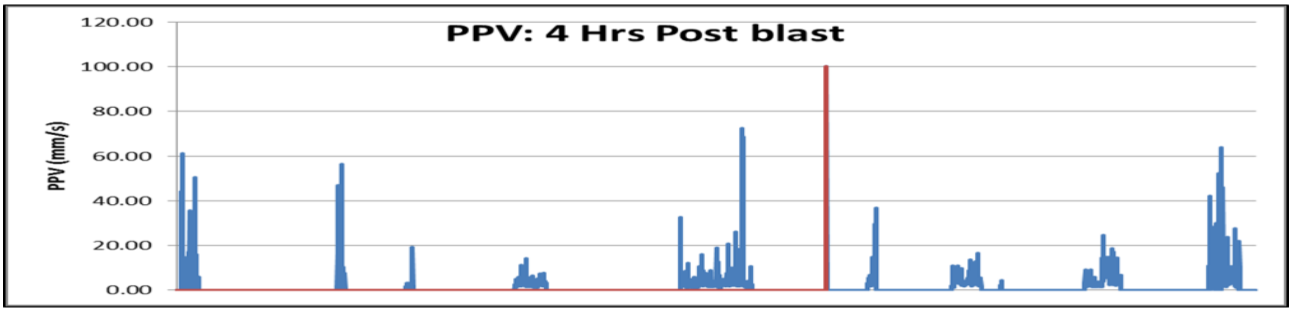

Figure 26: 8mW29W4 4 hours post blast

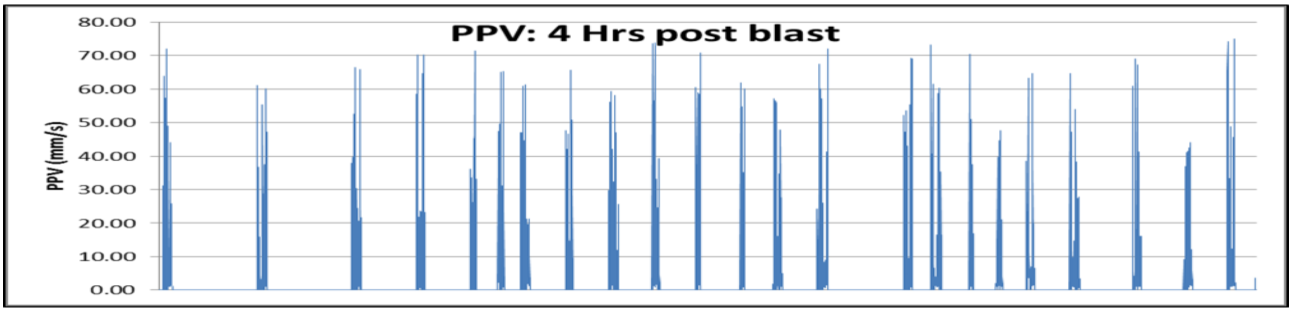

Figure 27: 8mE22E2 4 hours post blast

The differences between the post blast graphs are much more pronounced. It should be noted that the time interval for the E22E2 is a full month, subsequently the amount of events noted are not considered as a discrepancy. The following observations are noted:

1. Post blast clustering of events is denser at the primary monitoring sites. The second graph, 29W4, shows a definite increase in both amount and PPV prior to the Rock Engineer's inspection (denoted by the red line).
2. At the 29W5 site an initial decrease in events and PPV is noted but a period of sharp increase in both amount and PPV is noted. It is reiterated that the entire data set for the 29W5 site has been recorded in the absence of stoping production blasts.
3. For the 22E2 site the amount of events as well as the average PPV appears to be more and larger respectively. What does set this data apart from the primary sites is the consistency of the event clustering and PPV.

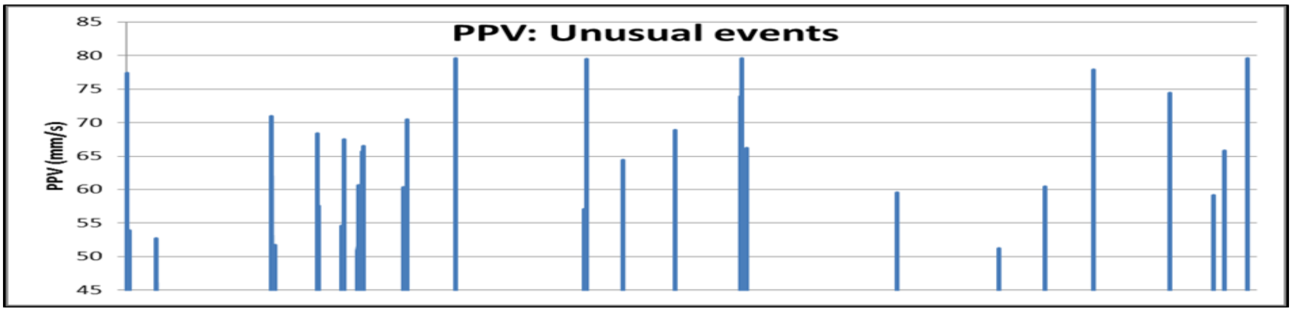

Figure 28: 8mW29W5 Unusual events

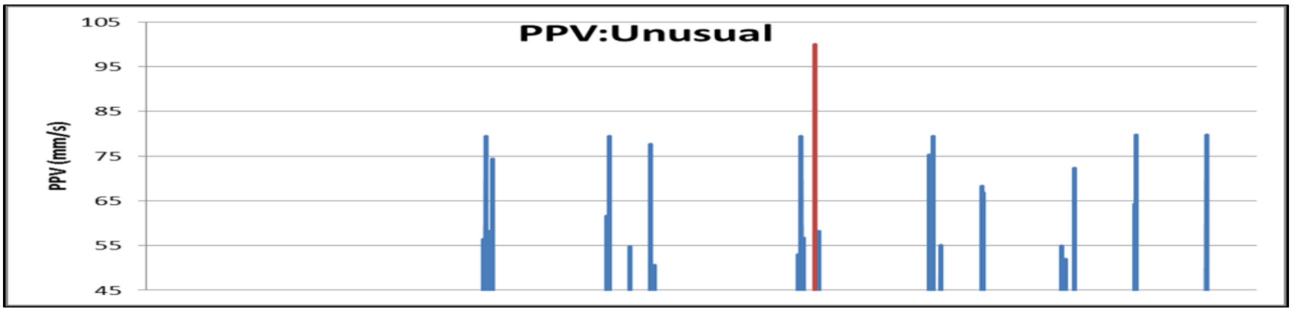

Figure 29: 8mW29 W4 Unusual events

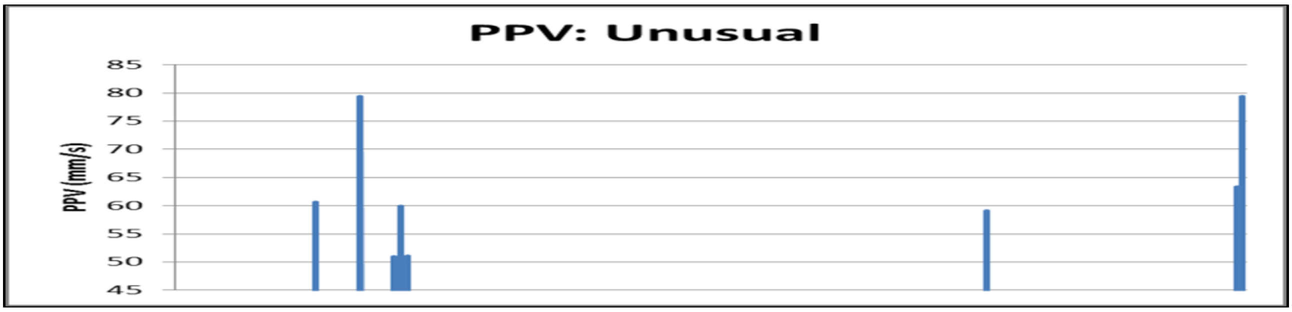

Figure 30: 8mE22E2 Unusual events

Again, there are noticeable differences between the graphs. The following remarks are made:

1. The first and most apparent difference between the primary sites and the control site is the relative absence of "unusual" events.
2. At the 29W5 site a reasonably consistent pattern is present which is similar to the profile obtained from the 4 hour post blast plot.
3. At the 29W4 site the onset of "unusual" events was recorded shortly prior to the mining personnel reported deterioration in the ground conditions. Also notable is that after onset the occurrence of "unusual" events does not cease but rather continue occurring with a consistent pattern.

6 Conclusions and hypothesis

The actual field observations clearly indicate that the failures observed involved some degree of stress related damage. Typically stress related damage would not be regarded as out of the ordinary but since these cases involve a mining depth of less than 300mbs it is definitely noteworthy.

The expected virgin stress levels and even measured stresses (Stress measurements were conducted some time ago for an unrelated project at the same shaft) do not indicate sufficient magnitudes to initiate the type of damage observed. Of note, however, is the k ratio which has been confirmed to be in the region of 1.8.

Two other observations from a geological perspective are the orientation of the fall of ground trend along a major fault zone and the presence of a major intrusive body in close proximity to the highest density of collapses.

From the Platmine report two statements are also emphasised. The first is that massive unjointed rock masses have the ability to store large amounts of tectonic stress and secondly, high stresses are encountered near geological disturbances. In both cases the Anorthosite rock type has proven to be more prone to act as a “stress battery” storing large magnitudes of stress.

Taking the above statements into account as well as the initial observations from the micro seismic monitoring the author, at this stage, dares to speculate.

Firstly, on a geological level, two structures that may cause elevated stress levels are present namely a major fault zone and an intrusive body. By the nature of formation the IRUP intrusive body can be the source of anomalous stress conditions due to the lateral loading imparted in the rock mass during the intrusion process. Where a rock type with a stress storage capability, like Anorthosite, is loaded by the intrusion the result is a specific rock layer in which the pre-mining state of stress may already be relatively high. The incremental addition of induced stress by mining may be sufficient to cause the stress related behaviour observed.

The observable rock mass response is described relatively easily but the actual panel scale failure mechanism is not yet described. It is here that the micro seismic data can give insight. It should be noted that although only PPV plots have been included various other parameters are still being analysed. These include energy released, magnitude, application of Omori’s law as well as the inverse thereof to determine aftershock sequences is to name a few.

When comparing the all-inclusive data plots the most prominent feature is the consistently higher PPV associated with the blast measured at the control site. As a first assumption this may be indicative that at the primary control sites wave propagation through the rock may be hindered as a result of elevated stress levels.

Considering the post blast plots the existence of consistent patterns at the primary sites indicate that once stress levels reach a certain boundary a system of load shedding is initiated. As is seen at the 29W5 site it appears that this load shedding continues even after the stope face ceases to advance. Also, the onset of such a load shedding system daylights into the excavation in the form of a sudden onset of severe fracturing of the face and immediate face area hanging wall. Figure 10 clearly illustrates the fracture surface which originates from the stope face.

The “unusual” plots further strengthen the notion of a load shedding system. At both the primary site consistent patterns can be observed. It appears that this occurrence is not much concerned with time of day nor even face advance. The process can be described as a continuous in a sense.

It also appears that, although continuous, the system is not necessarily deteriorative. Of the two primary sites described one is currently still mining and the other, although abandoned, is still stable.