SEISMOLOGY AND SLOPE STABILITY IN OPEN PIT MINES

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ABSTRACT

The implementation of routine real-time micro-seismic monitoring of open pit mine slopes has been discussed. Some examples of seismic arrays have been given, and a recommendation of suitable seismic sensors made. Unfortunately near-surface sensors are required for good location accuracy, and the effects of reflection, mode conversion and surface waves must be accepted and compensated for during processing of the seismograms. It makes sense that mining at the base of a slope and levels of seismic activity within the slope should be related, and this is confirmed using both 2002-2003 and 2005 seismic data recorded at Navachab mine. An example of how seismic data can be used to gain information about seismically active geological structures has been described. The removal of broken rock, and not blasting nor the breaking of supporting rock, has been found to cause slope micro-seismicity. While the standard Brune source model is suitable for some 20% of the seismic events, unreasonable results are obtained for the rest. A moment tensor inversion has been performed after S-wave splitting and surface effects have been filtered out. This approach confirms a predominantly shear mechanism for a typical high frequency source.

1. INTRODUCTION

Micro-seismic monitoring of open pit slopes has been routinely practiced since 2002 at various mines in Namibia, South Africa and Australia. At such mines, slope monitoring is also carried out using standard surface deformation measurements of surface points. However, it can be difficult to identify future potential failure mechanisms from the 1-dimensional surface data, no matter how accurately such data is being obtained, and so the 3-dimensional nature of micro-seismic data is appealing.

Brittle fractures in rock radiate seismic waves. If these waves can be recorded sufficiently clearly as seismograms by a number of sensors, the seismic event's origin time, location and source parameters such as fracture dimension and average slip can be estimated. While the technique is commonplace in underground mining operations (see for example Mendecki *et al*, 1997 or van Aswegen *et al*, 2000), it is only recently that technological advances have enabled routine micro-seismic monitoring in the open pit environment. Seismic events can now be located and quantified in the 3-dimensional volume of the rock slope, opening the door to a deeper understanding of how mining is affecting the slope.

Measurements have been taken at more than 25 open pit slopes to date and all contain signatures of brittle rupturing. In one case, a slope height of 80m was enough to generate recordable micro-seismicity. In another, a soft wet rock slope with intact UCS values of 20-50 MPa was also causing recordable micro-seismicity. These extreme cases indicate that routine micro-seismic monitoring may be possible in most open pit slopes.

Previously, a good correlation has been observed at the Navachab and Union Reefs open pit mines between slope surface movements and the seismic event data recorded within the slope (Lynch et al, 2005). Knowledge of the fracture locations and sizes is converted to inferred surface movements using a simple expression, and the inferred movements have a time advance of 1-2 months – areas of the slope indicated by seismic data to be moving are measured to be moving some 1-2 months later. The reason for this time advance has been attributed to the rheology that arises from the many rock inhomogeneities – movements from fracturing within the slope take time to appear on surface.

This paper gives a brief overview of how routine real-time micro-seismic monitoring of open pit slopes is implemented. The typical seismic arrays, monitored volumes, seismic station technology and data transfer, processing and reporting are discussed. The link between mining at the bottom of a slope and levels of fracturing recorded within the slope is explored. Seismic data can be used to gain information about seismically active geological structures, and this is exemplified using some data from Navachab mine. The question “What causes open pit slope fracturing: blasting, support rock being broken or removal of rock?” is answered using some data from Sunrise Dam mine. The Navachab seismicity can be divided into two groups: predominant high frequency events are well fitted by the Brune model with physically reasonable results. The Brune model gives unreasonably large crack dimensions and low slips for the low frequency events. Surface effects and S-wave splitting are avoided with a moment tensor inversion using band-pass filtered data from the deep sensors and predominantly shear mechanisms are confirmed for the typical high frequency sources.

2. TYPICAL ARRANGEMENT OF ROUTINE SEISMIC MONITORING

2.1 SEISMIC ARRAY

For seismic events to be reliably located by an array of seismic sensors, the sensors should surround the volume of rock being monitored. In an open pit environment, this requirement means that sensors must be located near to the surface as well as at the bottom of the monitored volume. The sensors are usually installed into a combination of long inclined and short vertical holes. Typically the entire pit is not monitored, but rather the slope suspected of potential instability.

It is unfortunate that near-surface sensors are required for reliable event location since the presence of nearby free surfaces cause strong reflections, P-to-S mode conversions and surface waves. These effects significantly complicate the processing of seismic data, and care must be taken to avoid serious systematic errors in estimation of source parameters.

Some open pit seismic arrays are shown in Figures 1 and 2. The typical distances between sensors would be of the order of 100-200 m, and the dimensions of the monitored volumes would be about 400 m × 200 m × 150 m. The near-surface sensors can be installed into short (10 m) vertical holes, and would be 4.5 Hz geophones. Since these sensors cannot be installed into holes inclined beyond 2° from vertical, 14 Hz omni-directional geophones are used for the long (100-300 m) inclined boreholes. Geophones are preferred to accelerometers since the typical frequencies recorded from slope seismic events are in the 10-400 Hz range, and geophones are more sensitive to this band. In addition, accelerometers are less reliable and, since the sensors are permanently grouted into these long, expensive boreholes, reliability is a serious issue.

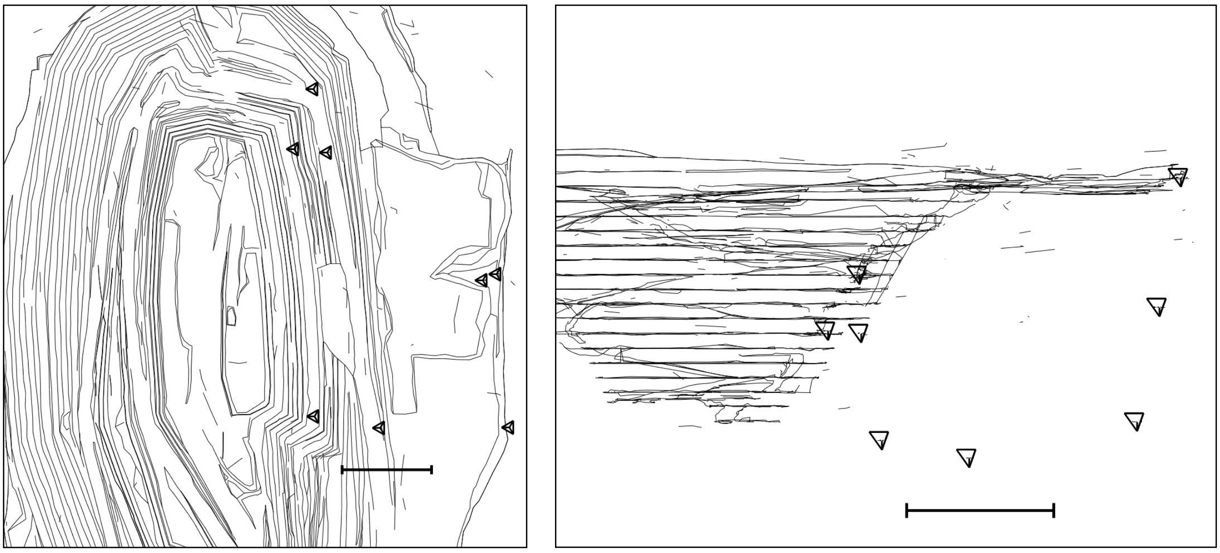

Figure 1: A plan view (left) and side view looking north (right) of the seismic array at Navachab gold mine in Namibia. A scale bar 100 m in length is visible in each picture. The tri-axial geophones are indicated by triangles.

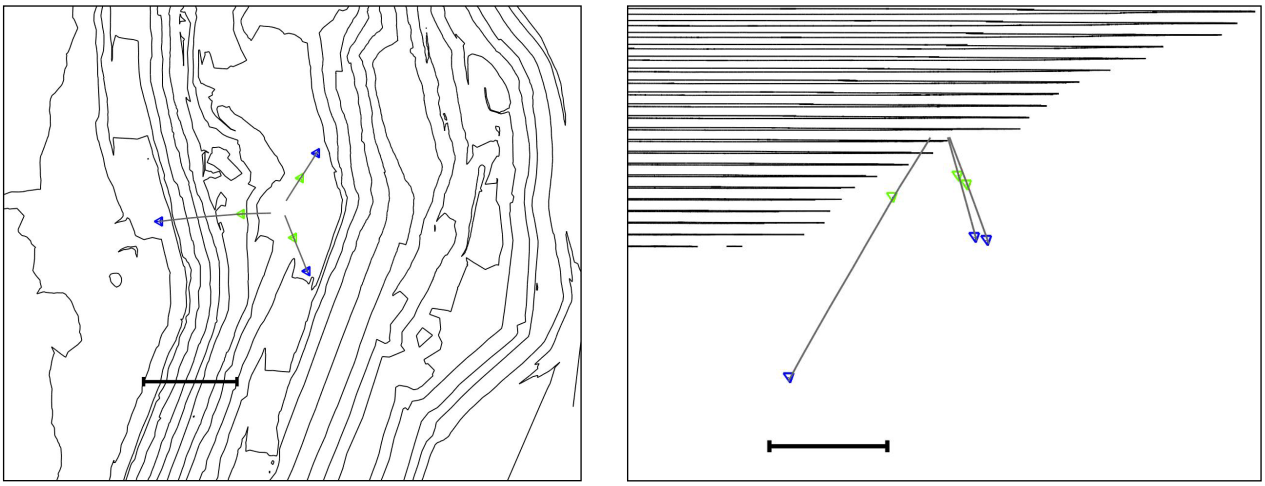

Figure 2: A plan view (left) and side view looking north (right) of the seismic array at Sunrise Dam gold mine in Australia. A scale bar 100 m in length is visible in each picture. The tri-axial geophones are indicated by triangles.

2.2 DATA ACQUISITION

Signals from the seismic sensors are monitored by StandAlone QS data acquisition units (ISSI, 2001). Since the signals can be very low amplitude (peak ground motions of 1 μm/s are common), a wide dynamic range is required to accurately monitor micro-seismicity in slopes. The signals are typically sampled at 6000 Hz with a 24-bit analogue-to-digital (A/D) converter, and time is synchronised across the network via GPS timing signals. To minimise the risk of lightning-induced damage to the sensitive A/D's, one station is usually sited at the top of a long borehole, and exposed sensor cable runs are limited by only monitoring the sensors in that borehole. Digital radios enable real-time two-way communication with the central computer in the geotechnical offices, and 100 W solar panels are sufficient to power the seismic station. The stations report each trigger, and if several stations have triggered in a consistent manner, the seismogram is requested and transferred to the central computer for processing and storage.

2.3 DATA PROCESSING AND REPORTING

The kind of fast internet connections commonly found on mines these days allows the seismic data to be automatically sent to a remote central facility for processing and analysis. For each seismic event the origin time, spatial location and estimates of the source parameters are computed. After routine analysis of the seismic event data, regular reports are then sent back to the mine geotechnical engineers for interpretation along with other geotechnical data. This kind of data processing and analysis is now routine for mines in Australia, South Africa and Namibia, and circumvents the need for advanced seismology training for the on-site geotechnical engineer.

3. ORIGINS OF SEISMIC EVENTS IN OPEN PIT SLOPES

3.1 MINING RATE AT PIT BOTTOM AND SEISMIC ACTIVITY

Intuitively one would expect that mining activities have an influence on levels of fracturing within a slope – the deeper a slope is, the more stressed and therefore the more it fractures. Seismic data confirms this link, and goes further by providing a monitoring tool to quantify the effects mining is having on the slope. Answers can be provided to questions such as "will mining 500,000 m^3 from the opposite side of the pit have a stronger or weaker effect on the slope than mining 100,000 m^3 from the bottom of the slope?"

An example of this correlation may be found in the seismic data recorded at Navachab mine. A plot of cumulative number of seismic events recorded in the Navachab eastern slope from April 2002 until January 2004 shows 2 distinct periods of increased micro-seismic activity: October 2002 to January 2003 and June to September 2003. This graph is compared with the time history of mined rock at pit bottom over the same time period in Figure 3. A good correlation between the two graphs is observed. This correlation between levels of fracturing in the slope and mining at pit bottom is consistent with expectations. Rainfall, typically between November and March, does not appear to influence slope fracturing to the same degree.

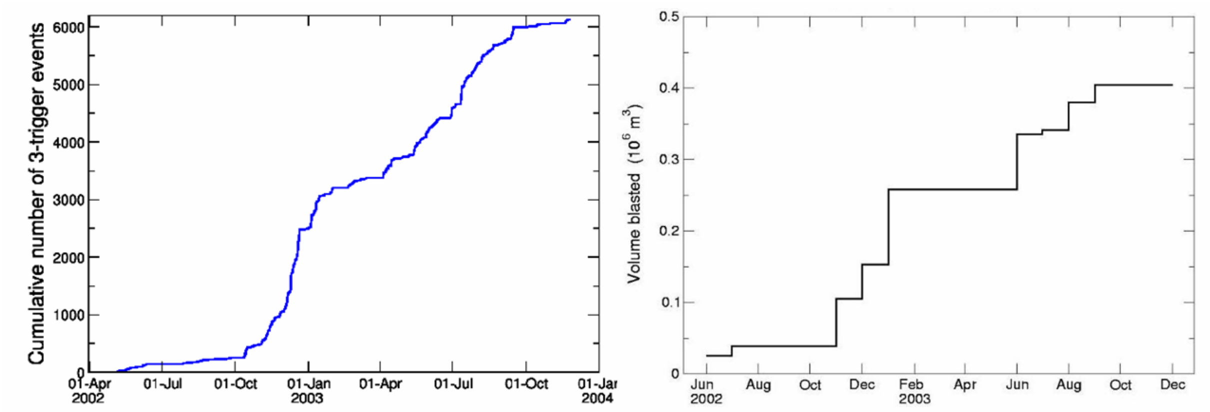

Figure 3: Graphs of the cumulative number of seismic events (left) and the cumulative amount of rock removed from the bottom of the pit (right) as functions of time. The general forms of the two graphs are similar.

As another example of this correlation, the seismic activity recorded and accepted after processing in 2005 is examined. During this time the pit was being deepened, and the cumulative amount of rock removed below certain elevations is shown on the same time axis as the cumulative number of seismic events – Figure 4. It appears that the slope responds quite strongly to mining below about 995 m elevation – a pit depth of about 170 m.

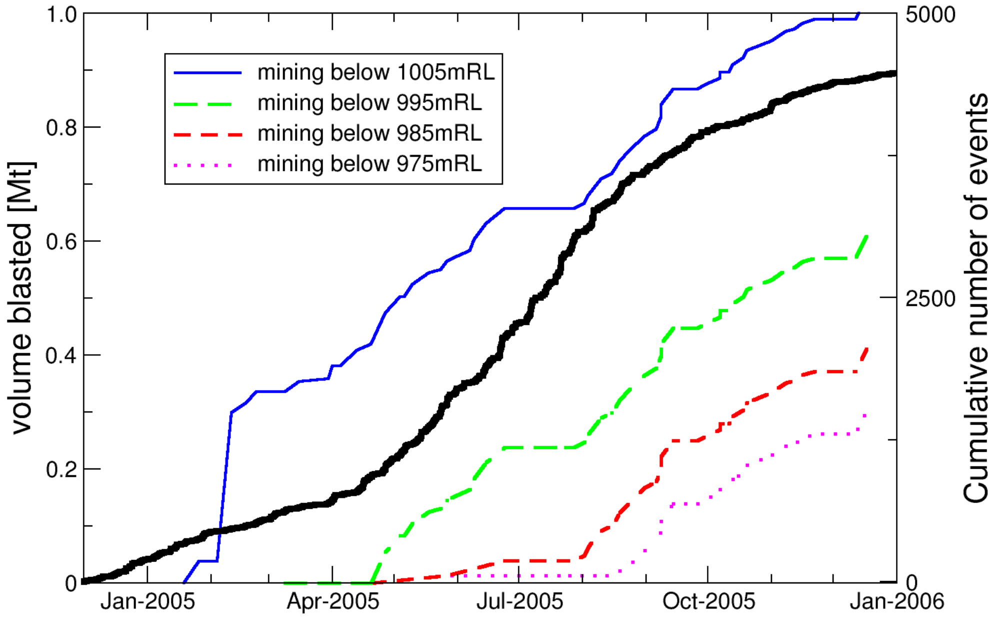

Figure 4: The cumulative amount of rock removed below the 1005, 995, 985 and 975 levels as functions of time (left vertical axis). Also plotted is the cumulative number of seismic events recorded and accepted after processing (thick line, right vertical axis).

3.2 SEISMIC EVENTS ON GEOLOGICAL STRUCTURES

Simple FLAC2D modelling was carried out for the Navachab pit (Lynch et al, 2005). It was found that the stresses at the bottom of the 180 m eastern slope were not high enough to cause fracturing of the intact rock. Therefore the recorded micro-seismic activity had to be structurally related, with these structures obviously being weaker than the intact rock.

The located seismic events would tend to lie on a particular group of geological structures if those structures were responsible for the fracturing, and so a search for statistically significant planes of weakness in the seismic data is useful. When this procedure is applied to the Navachab data, a plane sub-parallel to the slope is indicated – Figure 5. Since this plane has a very similar dip and position to the major J2 joint set, it is assumed that these structures are slipping, resulting in the recorded seismicity. The unfortunate orientation of the joint set makes extension strain (Stacey et al, 2003; Popov, 1990),the most probable failure mechanism indicated by modelling, the likely culprit here.

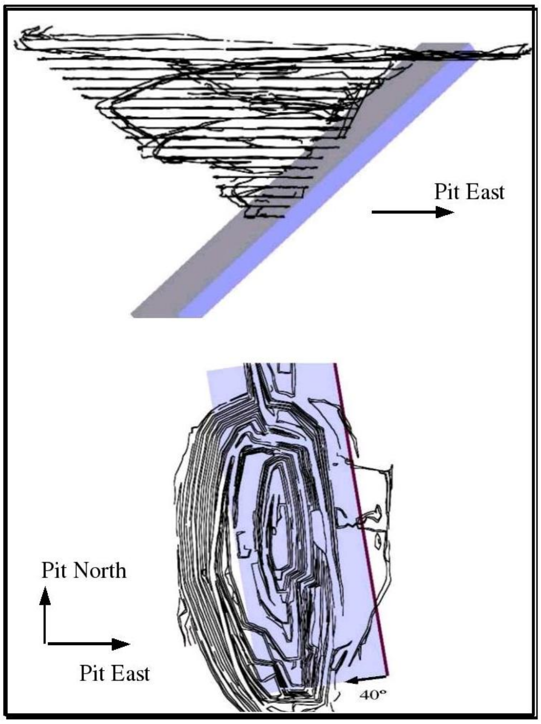

Figure 5: The most statistically significant plane found in the seismic data from May 2002 to November 2003

3.3 SEISMIC ACTIVITY FROM BLASTING AND LOADING

It seems clear that micro-seismic activity recorded in open pit slopes is related to mining rates near the slopes. The fracturing itself could be caused by blasting (the dynamic elastic wave generated could trigger fracturing), de-coupling of the broken rock from the slope (the broken rock now rests against the slope bottom, whereas before the blast it was part of the slope) or loading and removal of the broken rock (stress changes caused by the missing weight). The question to this issue is found in some data recorded in an Australian open pit mine during April-May 2005. Two blocks of rock totalling about 100,000 bulk cubic meters were blasted and removed in late April and early May 2005. The area of the mining was directly below a slope being monitored with a small micro-seismic array. This is shown in Figure 6.

Figure 6: Plan view (North at the top) of the mining area beneath a part of the eastern slope being monitored with a micro-seismic system. The blocks indicated (504 to the North, 506 to the South) were blasted and loaded in April and May 2005.

The cumulative number of seismic events recorded, processed and accepted during this period is shown in Figure 7. A small jump in seismic activity is evident very soon after the second blast, but the really significant increase in micro-seismic activity is observed 2 days after the last blast. This alone indicates that transient loading due the dynamic elastic waves of the blast is not causing any significant fracturing within the slope.

A graph of the amount of broken rock removed vs. time is shown in Figure 8. The micro-seismic activity increases after about 130,000 tonnes have been removed from both blocks (75,000 from block 504 and 200,000 – 145,000 = 55,000 tonnes from block 506), and stops abruptly as the loading and removal ceases. Evidently stress changes caused by unloading the bottom of the slope plays the dominant role in generation of micro-seismic activity.

It is possible that the slope was relaxed before the first blast, and absorbed some stress changes elastically before fracturing commenced. The short time period between cessation of unloading and the drop in seismic activity indicates that this slope does not have significant rheology, and stress changes are quickly distributed throughout the volume, as happens in a purely elastic medium.

The micro-seismic array was installed in this place to monitor a possibly problematic shear zone that lies roughly sub-parallel to the slope here, about 50m beneath the surface. A side view of the seismic event locations during this period of unloading and resultant high seismic activity (Figure 9) shows that the bulk of the located fracturing is taking place beneath the level of the pit floor, and so the shear zone was not mobilised by this mining.

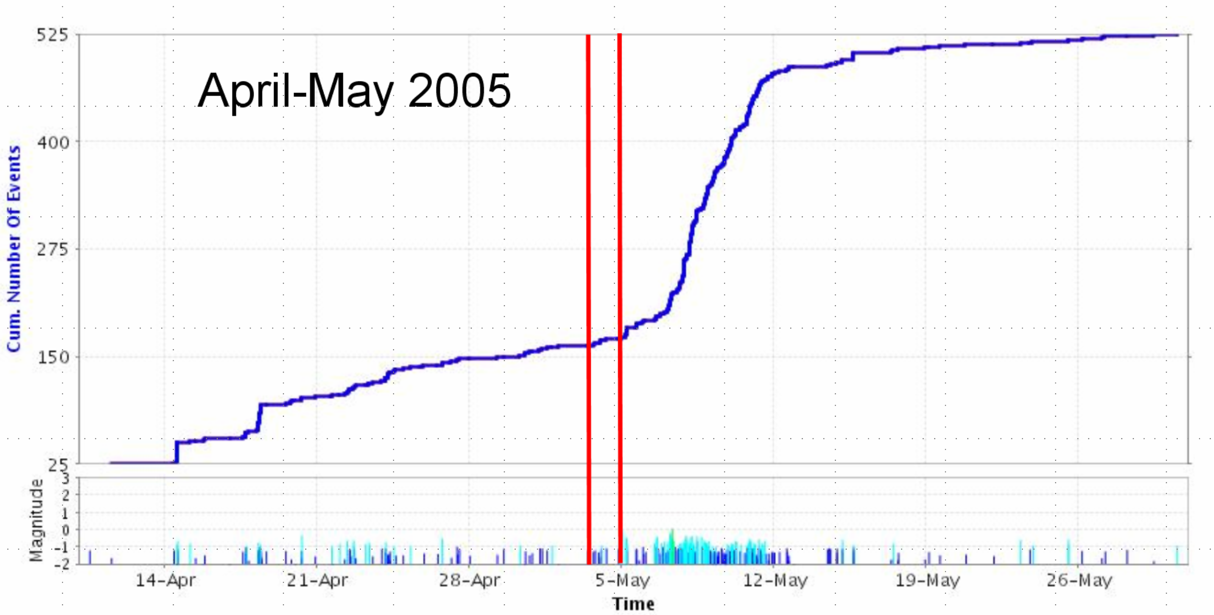

Figure 7: Cumulative number of recorded seismic events as a function of time. The times of the two blasts at the bottom of that slope (blocks 504 and then 506) are indicated by the vertical lines. Evidently micro-seismic activity is not related to the transient loading of the dynamic elastic wave from blasting.

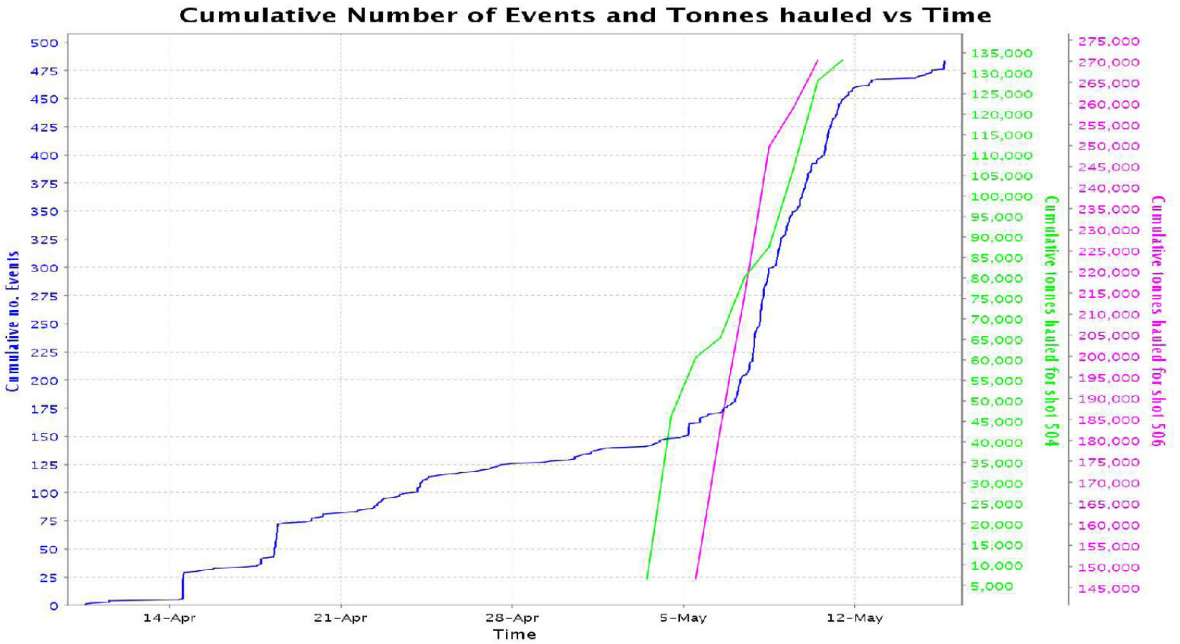

Figure 8: The cumulative number of tonnes removed from blocks 504 and 506 after blasting. The seismic response appears to start when about 75,000 tonnes has been removed from the 504 block and 200,000 – 145,000 = 55,000 tonnes have been removed from the 506 block. The seismic response stops abruptly when the removal of broken rock is finished.

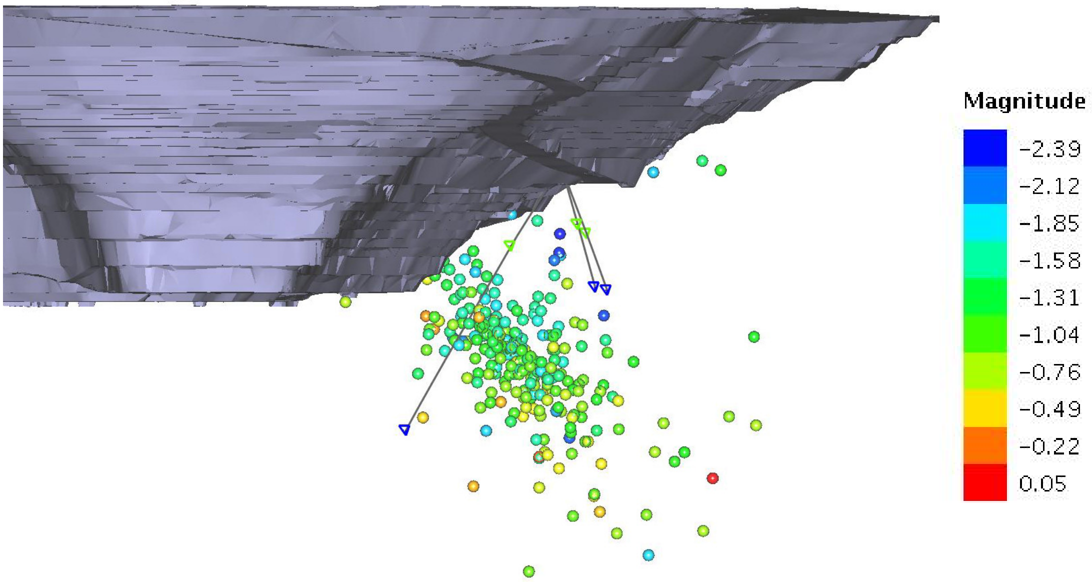

Figure 9: Side view (looking North) of the located micro-seismic events recorded during the seismic response to unloading of broken rock after the 504 and 506 blasts. The local magnitude scale is also shown. Most of the events occur beneath the floor of the pit. Interestingly, the major shear structure running roughly sub-parallel to the slope through the middle of the seismic array appears to be seismically quiet. This, combined with the absence of any surface movements, indicates relative stability of the shear zone here.

4. SEISMOLOGICAL ANALYSIS OF SEISMIC EVENTS RECORDED AT NAVACHAB MINE

4.1 HIGH AND LOW CORNER FREQUENCIES OF SEISMIC EVENTS

The micro-seismic events at Navachab are diverse in relation to the spectral content of their waveforms. The dominant frequency of the radiated seismic energy is typically between 10 and 400 Hz. It is useful to filter the recorded events into two groups based on the dominant frequency: a "low frequency" (LF) group with dominant frequencies less than 100 Hz and a "high frequency" (HF) group comprising the rest of the data. Seismic data from January, February and September 2005 was used in this analysis. The sources of the majority of events during this period of time were located in the vicinity of the bottom of the pit. The characteristic features of each of the two groups are presented below.

The HF group contains about 20 % of all events. Waveforms and spectra of a typical HF event are shown in Fig. 10a and Fig. 11a, respectively. Usually the arrivals of P- and S-waves are easily identified on these waveforms and as the result the location of these sources is quite reliable, with an average error of about 4 m. Some source parameter estimates are obtained using the Brune's circular shear dislocation model [Brune 1970]: fracture radius 2 to 11 m, static stress drop 5 to 50 kPa, and average slip across the fracture of 2 to 20 μm. The usually high ratios of S-wave energy to P-wave energy tends to indicate predominantly shear source mechanisms. These parameter estimates are quite plausible. Indeed the close similarity of these open pit waveforms to those recorded in underground mining environments implies that the standard processing techniques are quite reliable for this data.

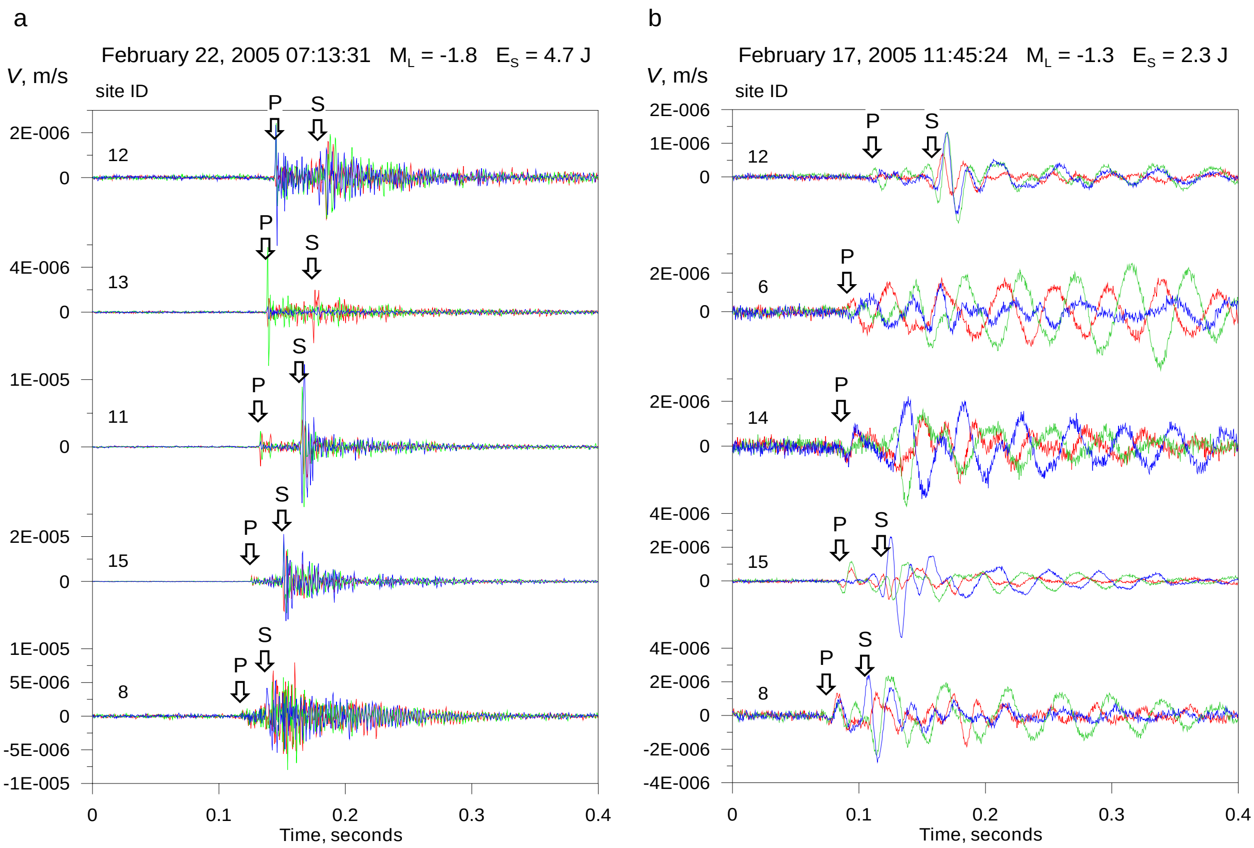

Figure 10: Waveforms of typical high-frequency (HF) (a, left) and low-frequency (LF) (b, right) events recorded at Navachab open pit mine. While the P- and S-wave arrivals are easily identifiable for the HF events, the LF events are more difficult to process.

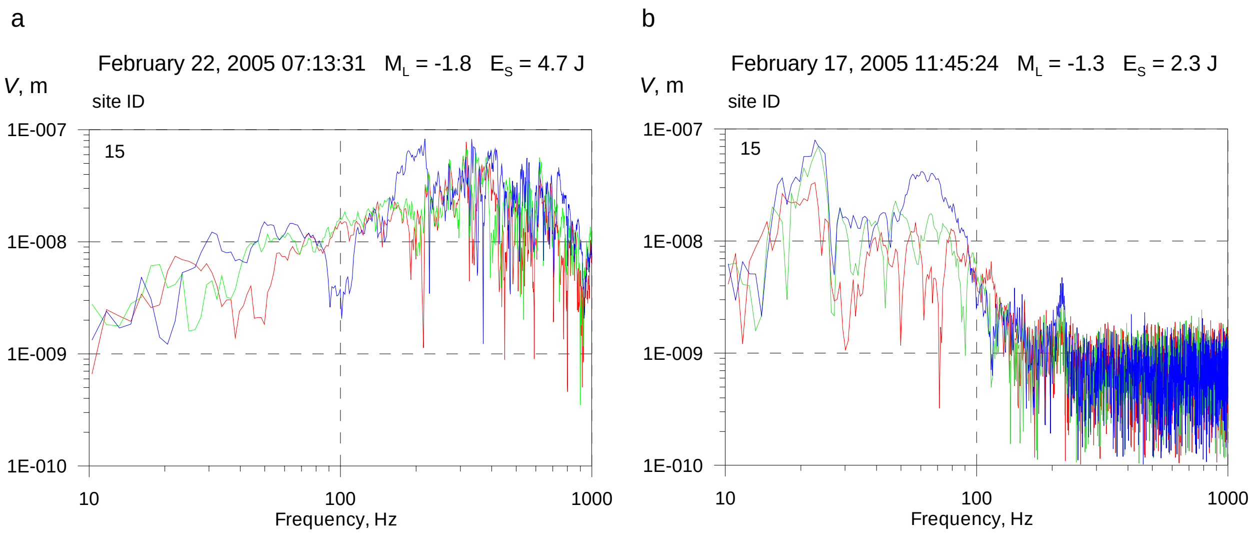

Figure 11: Spectra of the events shown in Fig. 10, recorded at site ID 15.

A day-of-week distribution of the HF events is sufficiently uniform (Fig. 12a), that it would appear that these seismic sources don’t correlate with loading and blasting operations in the pit - these activities did not take place on Sundays at this mine during the period of interest.

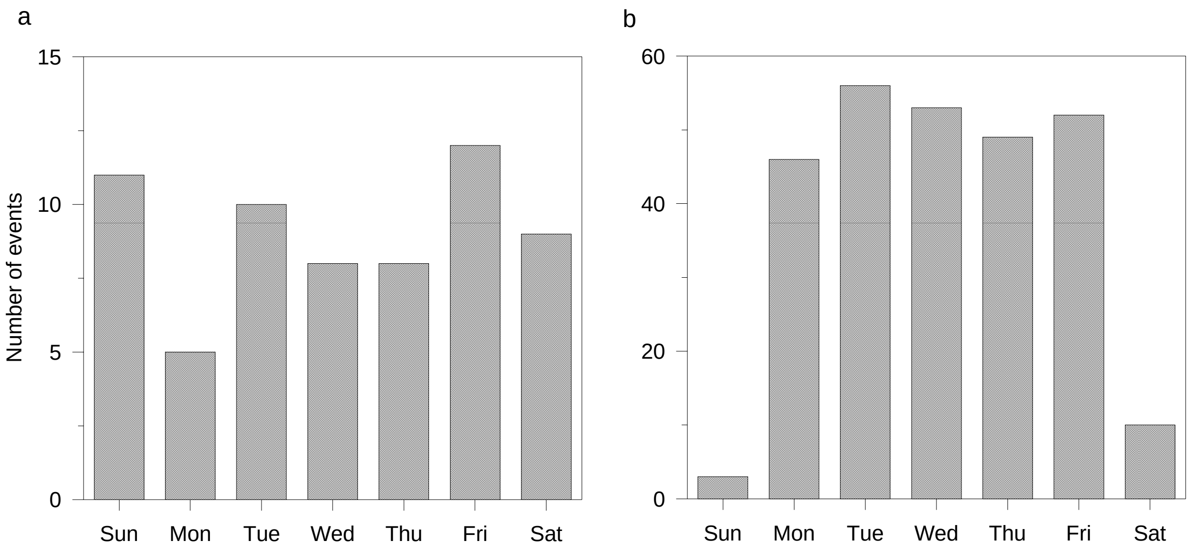

Figure 12: Day-of-week distributions of HF (a, left) and LF (b, right) events. At Navachab mine there is lower mining activity on Saturdays and practically none on Sundays, and so there is a good correlation of the LF events to mining.

The second group contains micro-seismic events with dominant frequency of signals lower than 100 Hz. Seismograms and spectra of a typical LF event are presented in Fig. 10b and Fig. 11b, respectively. Usually waveforms of these events for near-surface sensors (site ID's 6, 8, 10 & 14) are complicated by intensive surface waves [Lynch 2005]. These waves are clearly seen in fig. 10b as a slowly decaying vibrations with frequencies 10 to 30 Hz arriving after S-wave. Sometimes the presence of surface waves imposes difficulties on the identification of the S-wave arrival and reliable estimation of the source parameters. In some cases the low-frequency content of the seismic signals doesn't allow for identification of even the P-wave arrival. All these factors make location of the seismic source more difficult, and result in higher location errors than for the HF events. The average location error of the LF events is about 11 m. The processing of the waveforms in terms of Brune's model yields the following source parameter estimates: fracture radius 10 to 150 m, static stress drop 0.05 to 0.5 kPa, and average slip across the fracture of 0.02 to 0.2 μm. These parameter values do not seem reasonable. In particular, the ratio of source size to average slip seems much too high.

The day-of-week time distribution of the LF events (fig 12b) shows a close correlation with mining activities in the pit. This, combined with the unphysical source parameters, tends to indicate an artificial origin – perhaps noises created by mining activities. However the day-of-week distribution could also be explained as a result of seismic sources in rapid response to unloading the surface of the pit floor, as discussed in Section 3.3. The unlikely Brune's model parameters could also be discounted since there have been previous examples of the failure of the Brune model to describe genuine near-surface fractures (for example Prugger and Gendzwill, 1993 and Ming et al, 1998).

Since the LF events constitute an essential part of the observed seismicity (>80%), it is not efficient to simply exclude them from analysis as there exists the possibility that LF events reflect some specific fracture processes at the bottom of the pit. The best tool to further study these seismic events in order to obtain a correct description of the sources is inversion of the source mechanism in terms of the seismic moment tensor.

4.2 MOMENT TENSOR DECOMPOSITION OF A TYPICAL HIGH FREQUENCY FRACTURE

The seismic moment tensor $\mathbf{M}(t)$ gives a model-independent description of the geometry and intensity of the co-seismic deformation at the source. $\mathbf{M}(t)$ is connected with the far-field part of the radiated displacement wavefield $\mathbf{u}(\mathbf{x},t)$ via a Green's function $G(\mathbf{x},t)$, which describes the propagation of seismic waves in the medium:

$$u_i(\mathbf{x},t) = G_{ik,l}(\mathbf{x},t) * M_{kl}(t),$$

where $\mathbf{x}$ is the 3-dimensional position vector, and t is time. Subscripts $i,k,l = 1,2,3$ indicate the Cartesian components of vectors and tensors, with repeated indices implying summation as per Einstein's convention. Thus waveforms of displacement $\mathbf{u}(\mathbf{x},t)$ at some sensor sites and knowledge of the Green's function $G(\mathbf{x},t)$ allow estimation of the components of moment tensor $\mathbf{M}(t)$.

The construction of an adequate Green's function is a crucial component of the moment tensor inversion procedure. For the case of the Navachab mining environment the Green's function should take into account the geometry of the surface of the pit. This is exceptionally important for data from the shallow sensors which exhibit strong effects of the free surfaces in the recorded seismograms (see fig. 10b). Construction of the Green's function accounting for the exact topography of the various open pit free surfaces is possible but impractical. To avoid this, attention was focused on the data recorded at the deep sensors (site ID's 11, 12, 13 & 15). The wave paths between seismic sources at the bottom of the pit and the deep sensors are entirely within the solid rock mass, and thus use of the Green's function for a homogeneous isotropic medium is indicated. Nevertheless first attempts using the homogeneous isotropic Green's function with the waveforms recorded at the deep sensors did not give stable moment tensor solutions. This could be explained by:

- presence of anisotropy due to nearly-vertical layering of rocks behind the eastern slope of the pit. This kind of anisotropy can cause severe splitting of S-waves, which occurs when vibrations in one transverse direction are effectively in a different medium to vibrations in the orthogonal transverse direction. Such splitting cannot be reproduced by a homogeneous isotropic Green's function;
- occurrence of near-source scattering. For events in the vicinity of the bottom of the pit strong reflection from the bottom's surface could appear. In the case of using a homogeneous Green's function these reflected waves will be incorrectly described as a part of primary radiation of the source.

A reduction of the abovementioned effects of anisotropy is by working with the low-frequency part of seismograms. In that case splitting of S-waves should be less pronounced. The attempt to make an inversion in the low-frequency range (20-70 Hz) was successful. Fig. 13 demonstrates the quality of inversion for the HF event shown in fig. 10a. Here the fitting of the observed seismogram (band-pass filtered between 20 and 70 Hz) by a synthetic one is shown. The coefficient of correlation of observed and synthetic waveforms is 0.81.

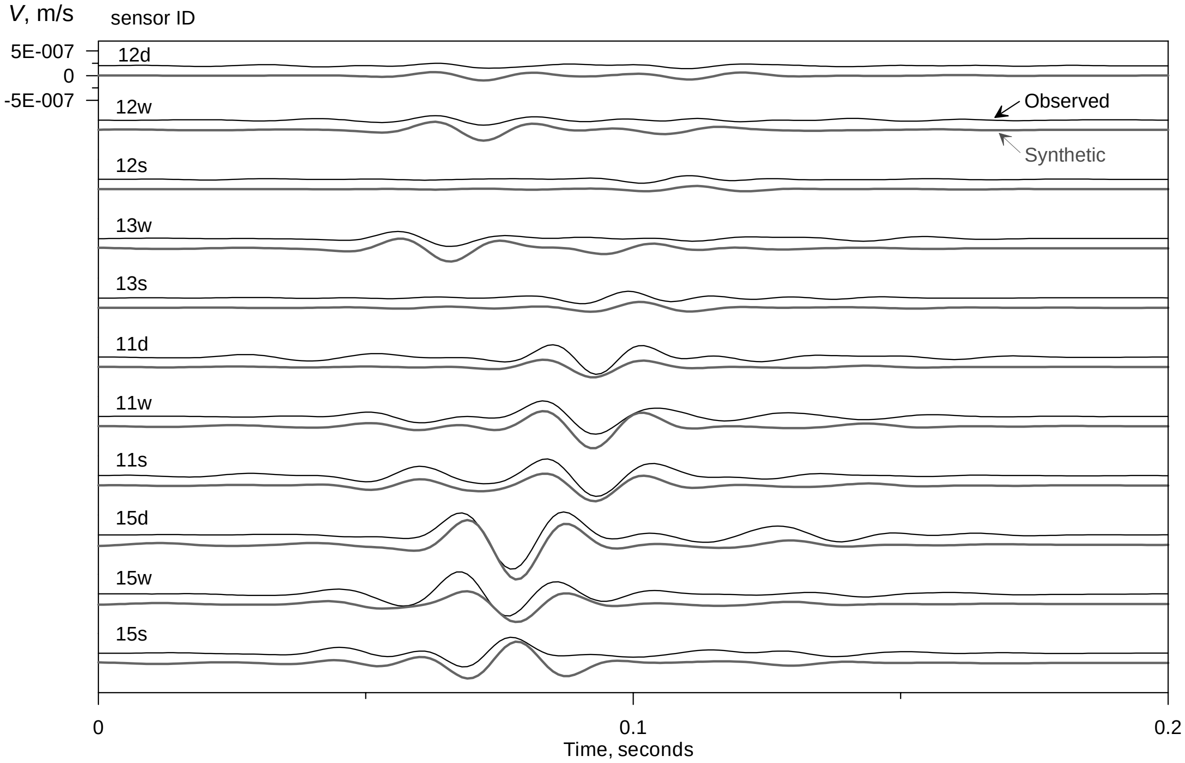

Figure 13: The band-pass (20-70 Hz) filtered seismograms of the event shown in Fig. 10a with synthetic seismograms obtained as a result of the moment tensor inversion. An acceptable correlation is evident. It would appear that the highly layered structure of the rock in the eastern slope at Navachab is causing some S-wave splitting, and hence the need for the band-pass filtering before a reasonable match with data can be obtained.

Decomposition of the inverted moment tensor according to the method of Knopoff & Randall (Julian et al. 1998) shows (Fig. 14) that it is essentially a double-couple description, which indicates a shear rupture with a small volumetric (tensile) component.

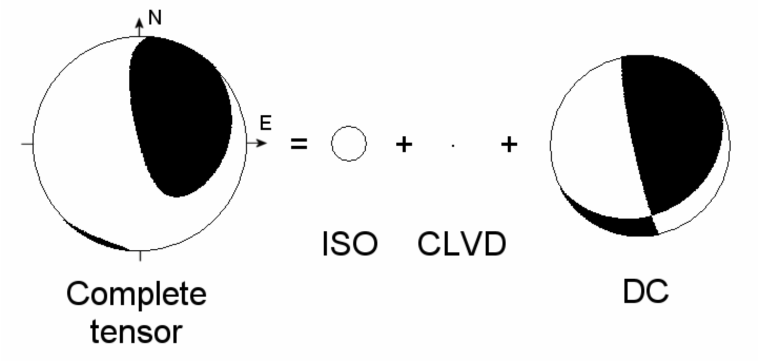

Figure 14: Decomposition of the seismic moment tensor obtained for the event shown in fig. 10a. The large double-couple (DC) component indicates a predominantly shear source mechanism.

5. CONCLUSION

Micro-seismic monitoring of open pit slopes is possible to implement routinely now that some technological hurdles have been overcome. Several early encouraging results have been obtained. These include good correlations between levels of micro-seismic activity within a slope and mining at the base of the slope, a match between seismic event locations and the suspected geological cause of the seismicity at Navachab and a good spatial agreement between areas of the slope indicated by seismic data to be moving and areas of the slope surface measured to be moving. Importantly, there appears to be a time advance between indications of slope movements from seismic data and the movements themselves. This time advance is most likely caused by the non-elastic nature of the slope, since movements deep within the slope take time to appear on the surface.

This work added to this body of knowledge by showing that slope seismicity appears to be the result of stress changes brought about by removal of the broken rock after blasting. Neither the transient loading by the dynamic elastic wave after blasting nor the slope response to some solid supporting rock being broken appears to be the cause.

In addition, fresh confirmation was obtained concerning the complex nature of seismograms recorded by near-surface geophones. Even the deep geophones appeared to be strongly affected by the layered geological structure at Navachab, with S-wave splitting being observed. For events with high corner frequency, the standard Brune model routinely used for all underground mine seismic monitoring appears to be valid. However, this model leads to unphysical estimates of source dimension and slip for the low frequency events. This phenomenon has also been observed elsewhere for near-surface seismicity, although no mention has been made of frequency dependence. More work towards a fuller understanding of the origin and source mechanism of the low frequency seismic events recorded in slopes is required.

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