Safety in Mines Research Advisory Committee

Final Project Report

Evaluation of the risk to underground mine personnel due to the rockmass response to continuous mining operations

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Executive summary

The object of the study was to determine whether there is a difference in the seismic response of the rockmass between 11-day mining cycle and full calendar operations - FULCO.

A literature survey was useful to gain insight in the time dependent rockmass response to mining. This helps to understand how the time of day distribution of seismic events can be affected by changes in mining operations. The literature survey did not contribute to the development of particular procedures for the difference in seismic hazard or risk between 11-day fortnight operations and FULCO.

We developed the simplistic concept of Seismic Exposure (SE). We define the hourly hazard as the average number of events greater than magnitude 1. The liability is the average number of workers underground during that hour. The average daily risk (daily SE) is the product of the hazard and the liability. The full risk for the period under consideration would then be the daily SE multiplied with the number of working days. This can be normalised by production for comparison purposes.

The general seismic hazard is described by conventional seismic hazard statistics. One advantage of a Gutenberg-Richter fit to the data is that the presence or otherwise of one large event need not influence the seismic hazard parameters. This helps to overcome a major problem with seismic hazard back analysis, namely the issue of single very large events that may or may not be included in a seismic events population because of a small change in the spatial or temporal filter parameter.

We introduced here an extension to the Gutenberg-Richter statistics by combining it with Energy-Moment statistics. Combining Gutenberg-Richter statistics, E-M statistics and empirically derived relations between strong ground motion and stress drop, the area is calculated over which strong ground motions could have exceeded a damaging threshold. This is the Potential Damage Area (PDA). The advantage of this parameter is that the hazard is expressed in a simple scalar number of m^2 which allows conventional arithmetic calculations, e.g. normalising by production.

The outcome of the study is tabulated below. It shows quite variable production figures for the different cases. Since, for the deep, hard rock mines, seismic hazard generally increases with production, normalising the hazard and risk parameters by production is considered fair. We express the risk in terms of daily Seismic Exposure and the general hazard in terms of PDA. The final comparison between 11-day fortnight and full calendar operations is then done by multiplying the daily SE with the number of production days and dividing it by the total centares mined. The Potential Damage Area is expressed as a percentage of the area mined.

		11-day Fortnight	FULLCO
Case A	SE/day	201.87	133.23
VCR	N prod. Days	273	349
'scattered longwalls'	PDA	1694	1794
FWR	Centares produced	202712	153129
	SE/centare	0.27	0.30
	PDA/centare x 100	0.84	1.17
Case B	SE/day	48.52	81.40
Main Reef	N prod. Days	234	301
Pillar mining	PDA	828	930
FWR	Centares produced	40105	50503
	SE/centare	0.28	0.49
	PDA/centare x 100	2.06	1.84
Case C	SE/day	115.99	228.08
Vaal Reef	N prod. Days	365	221
Pillar mining	PDA	266	209
Klerksdorp area	Centares produced	75110	85583
	SE/centare	0.56	0.59
	PDA/centare x 100	0.35	0.24
Case D	SE/day	86.57	166.16
Vaal Reef	N prod. Days	388	707
Scattered mining	PDA	444	2874
Klerksdorp area	Centares produced	106574	203671
	SE/centare	0.32	0.58
	PDA/centare x 100	0.42	1.41

Changing from 11-day fortnight operations to FULCO resulted in an increase in the Seismic Exposure per centare in all four cases. The percentage of the production area potentially damaged increased in two of the four cases and decreased in the other two. We thus do not observe a general increase in seismic hazard associated with the higher production achieved through FULCO, but we do find an increase in risk (Seismic Exposure) per centare mined.

A special analyses was also done, to test the notion that production days following breaks in production, like Mondays or other days after long weekends, are more hazardous than normal working days. If true, FULCO should at least be less hazardous in this respect. The results showed, however, the notion to be false. In fact, it appears that days following breaks are less hazardous than the average working day.

Acknowledgements

The research team is grateful to Durban Roodepoort Deep Ltd, African Rainbow Minerals and Goldfields Ltd. for access to data. Several individuals on mines in these groups had to devote time to find and present the required production data, manpower records and timing schedules. Anglogold kindly provided seismic data for testing the seismic hazard on days following breaks in production.

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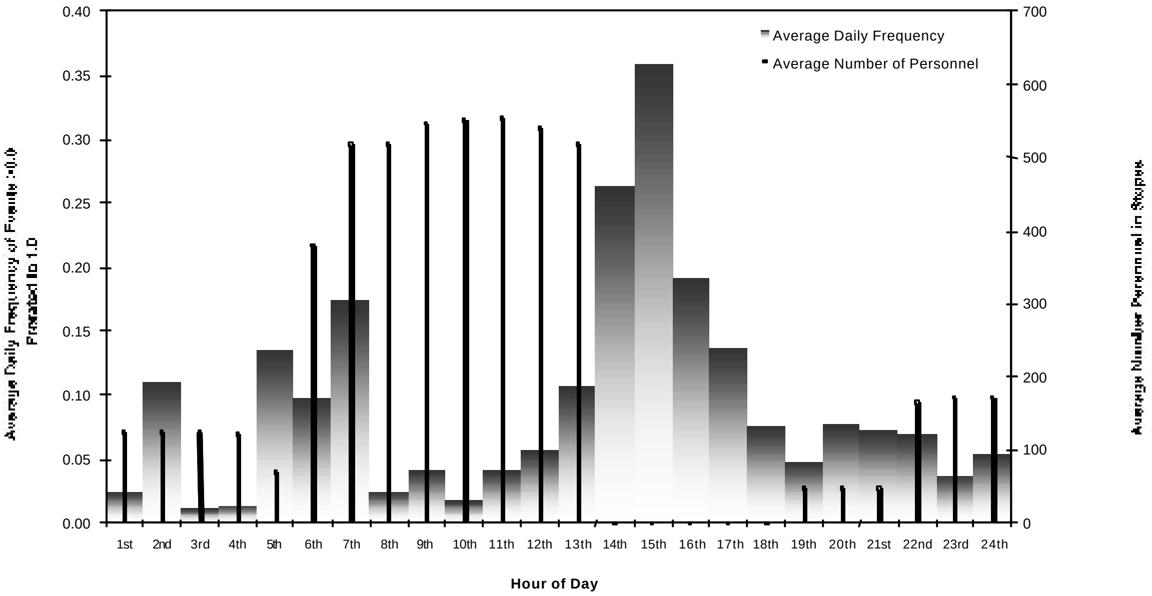
Average Daily Frequency
Average Number of Personnel
Average Daily Frequency of Events >0.0 Prorated to 1.0
Average Number Personnel in Stopes
Hour of Day
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0
100
200
300
400
500
600
700
1st 2nd 3rd 4th 5th 6th 7th 8th 9th 10th 11th 12th 13th 14th 15th 16th 17th 18th 19th 20th 21st 22nd 23rd 24th

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1. Introduction

With the introduction of full calendar operations in the South African gold mines (FULCO), an increase in productivity, i.e. rate of mining, is expected. All other factors being constant, it is likely that an increase in production rate should increase the seismic hazard (GAP303). An increase in seismic hazard means an increased probability for larger seismic events to occur, leading to an increased risk of rockburst and rockfall accidents.

These general statements should, however, be qualified. Examples could be quoted where increased levels of production were not accompanied by higher accident/incident rates. It has also been noted that frequent and irregular interruptions in production (weekends, long weekends, public holidays, strikes) cause interruptions in seismicity patterns which decreases the success rate of their analysis and interpretation.

Apart from the general seismic hazard, the timing of maximum hazard relative to blasting times is an important safety related phenomenon. It is general knowledge that the largest number of seismic events occur immediately after blasting and one could expect a decay of seismic activity following production blasting similar to the decay of aftershocks following major earthquakes (Omori law). On the other hand, because the processes leading up to seismic events are, to a certain extent at least, scale invariant in time, one could expect that the time delay after blasting would increase with magnitude, up to the point where the preparation time exceeds the time between blasts. In this case the triggering of imminent events by the sudden rockmass deformation caused by production blasting would increase the probability that the larger events would occur during or shortly after blasting. The specific rockmass response to production blasting is, furthermore, a function of system stiffness and the inherent rheological properties of the rockmass.

Because of the large number of variables in the system described above, it is important to quantify empirically the parameters describing the rockmass response to particular mining by blasting scenarios to allow valid statistical evaluation of seismic hazard/time of day and to provide possible input parameters to modern numerical models to increase fundamental understanding of the rockbursts and rockfall hazard associated with continuous mining by blasting.

The first part of the research deals with the concept of seismic exposure. It is an attempt to place the workers exposure to seismicity on a comparative basis for the two systems of mining.

The second criterion is the Gutenberg-Richter relation for three given case studies.

Based on the results of the case studies, conclusions are drawn on the differences between the two mining systems.

The influence of rate of mining was dealt with briefly in the past, resulting in a limited literature review.

The influence of a break in the production associated with the conventional mining cycle is also integrated using the Gutenberg-Richter *b*-value.

2. Literature review

2.1. Closure rates in conventional stoping

The rate of stope convergence, measured in between anchor points 16m deep into the foot and hanging-walls varies throughout the week. As expected, the highest rates of convergence occur during six hour intervals that include the times of face advance or blasting times - see arrows along the time axis at the Figure 2.1. The rate of convergence generally increases from Monday to Saturday, which suggests the stress relaxation is slower than face advance. After the last blasting of the working week, the rate of convergence diminishes considerably until the new blasting cycle on Monday (*Hodgson 1967; McGarr 1971*) Similar results were obtained by *McGarr and Green (1975)* by measuring the rate of a-seismic tilt as a function of the day of the week at ERPM.

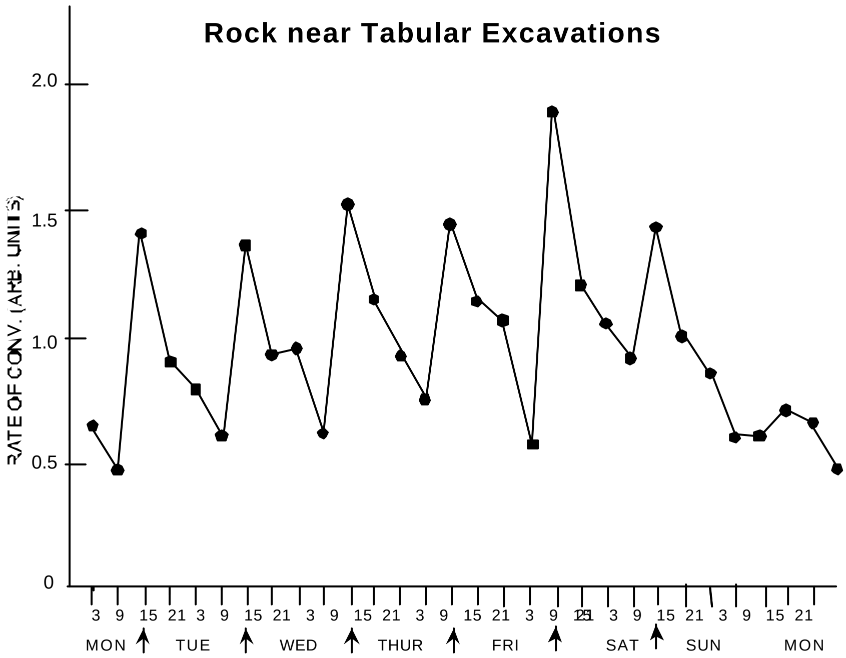

Figure 2.1. Convergence during six-hour intervals throughout the week. The experimental data have been averaged over 30 weeks. The time at the middle of a given 6-hour period is plotted on the abscissa; e.g. 3 corresponds to the period from 2400 to 0600. (After McGarr 1971, Hodgson 1967)

Figure 2.2 shows, in more detail, the experimental profile at the convergence rate (by McGarr, 1971) over a 42-hour period after blasting.

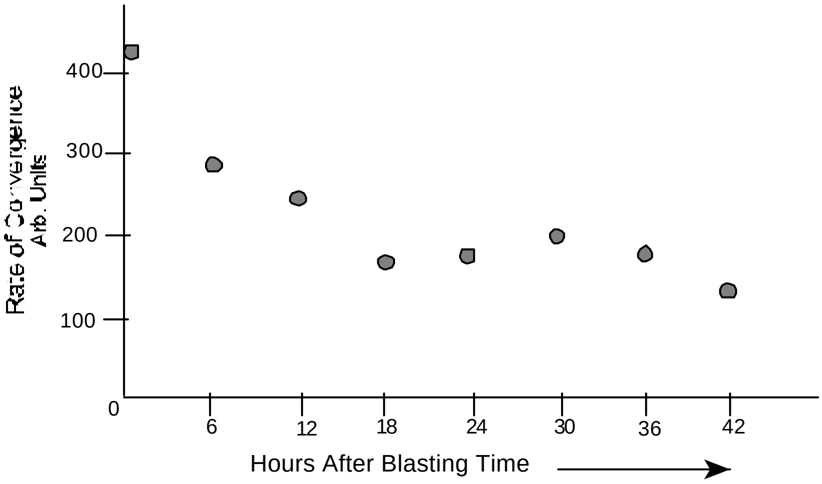

Figure 2.2. Convergence during six-hour intervals after the last blasting period on Saturday. (After McGarr 1971, Hodgson 1967)

Note the wavy character of the observations that the author is trying to explain by the cumulative error arising from adding a series of observations that are within the limits of measurability. However, the averaging process itself is a low-pass filter that should smooth the higher frequency components of the oscillations as opposed to enhancing it. Interestingly, observations of seismic deformation and/or activity rates after blasting, specifically for intermediate and larger events, frequently reveals similar wavy or multi-modal character in time domain – Figure 2.3. The relationship between the character of the relaxation function and the specifics of the blasting process is however unclear.

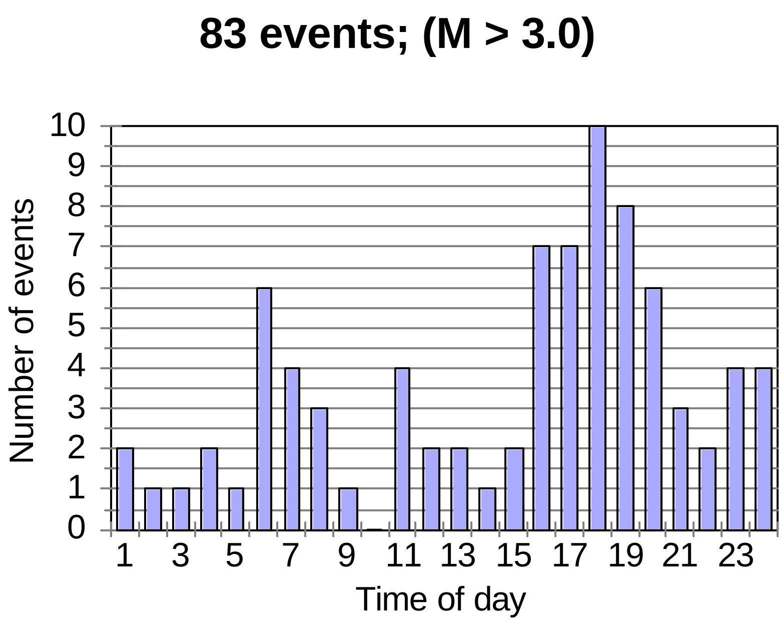

Figure 2.3. Time of day distribution of seismic events with magnitude m $3.0 at a SA gold mine averaged over a one-year period.

Size distribution of seismic events (by their magnitudes) at the beginning and at the end of the working week were shown reasonably parallel, on the Gutenberg-Richter plot, but the seismicity rate for Thursday and Friday were higher than for Sunday and Monday by a factor of about 2.5. It was concluded then that the observed increase of a-seismic strain rate during the week appears to affect *a*-value in Gutenberg-Richter relation but not the *b*-value. Thus, seismic hazard, say, measured by the recurrence time of events with magnitude not smaller than m, *Tr*($*m*), would be proportional to the rate of a-seismic deformation i.e. proportional to the rate of mining (*McGarr, 1976*).

Recent measurements in SA gold mines show basically three phases of closure after blasting: an instantaneous, followed by a primary phase (approximately 4 hours duration) followed by a long steady-state phase (*Malan, 1998 and 1999*). In all cases inspected, the closure curves are smooth with no indication of oscillations - Figure 2.4. Seismic hazard after the blasts however may not follow such a smooth exponentially decreasing line - see Figure 2.3, where over 15% of events with *m* $ 3.0 occurred approximately 14 hours after blasts between 6 and 8 o'clock in the morning.

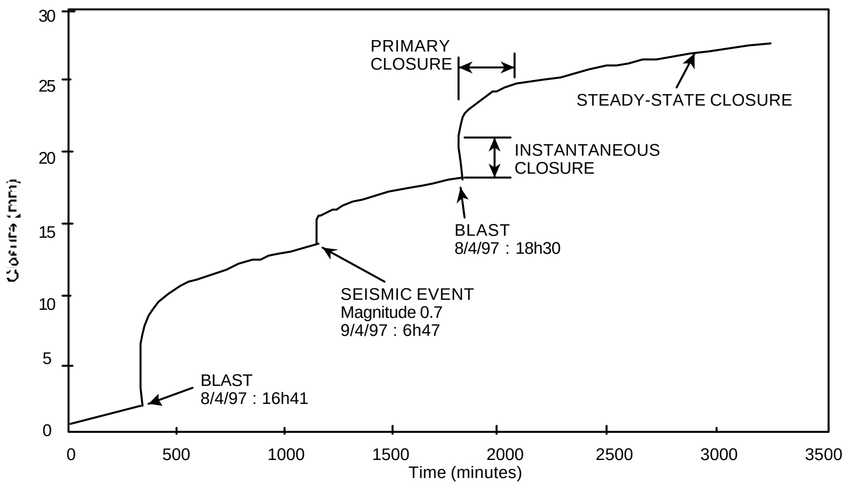

Figure 2.4. Typical time-dependent stope closure of the Ventersdorp Contact Reef at Western Deep Levels Mine. This was for a closure station at a distance of 8.7m from the face. (After Malan, 1999)

It is speculated here that the potential oscillations could have been discarded by the heavy low-pass filters imposed by both the clockwork closure instrument and by the fractured/ delaminated zones in the immediate foot - and hanging-walls (skin to skin type measurements). Some of the closure measurements done by *Leeman (1958)* at ERPM show a bimodal character, with the second phase commencing 6 to 9 hours after the blasts.

2.2. Conceptual Model to Quantify Seismic Rock Mass Response to Production Blasting and Associated Hazard

The following conceptual model has been developed under GAP601 and is repeated here for the sake of completeness. This project, GAP610, will deal with the influence of FULCO on the relaxation processes in time domain and associated hazard and seismic safety risk.

To quantify seismic rock mass response to blasting one needs to consider its size, time and spatial distributions. The size distribution of seismicity can be described by the activity rate and by the power law exponent *a* and the *b* values of the Gutenberg-Richter relation. To understand spatio-temporal dynamics it is helpful to distinguish the following three characteristic length and time scales:

– the excitation length and time
– the relaxation (dissipation and diffusion), length and time
– the correlation length and time

It is the ratios of these lengths and time scales to each other and to the characteristic system size, *L*, that will determine the state of the dynamics of the system - see Figure 2.5.

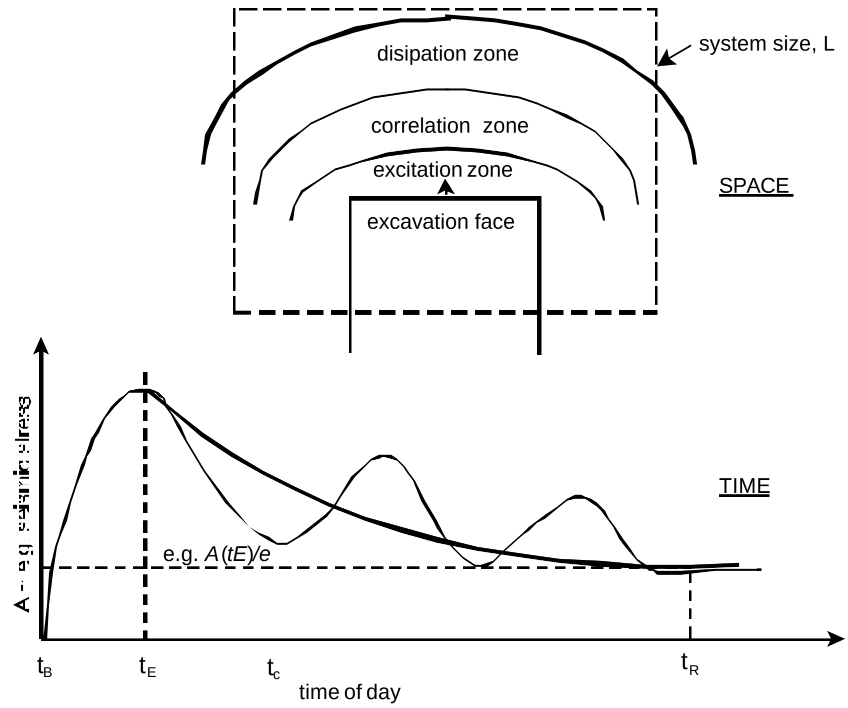

Figure 2.5. Conceptual spatio-temporal model of seismic rockmass response to production blasts with smooth (thick line) and wavy (thin line) character of the relaxation processes. (After GAP 601a)

The excitation length and time, l_E and t_{E1}, characterise the scale on which energy is injected into the system by external forces and/or by intrinsic instability, e.g. by the combined effects of blasting and the instantaneous convergence, or by the larger seismic events.

Practically the excitation time can be defined as the time for the rock mass ahead of the face to reach its maximum stress after the blasts. The excitation length then would be the spatial extent of seismic activity during the excitation time.

The relaxation length and time, l_R and t_R, characterises the minimum scale on which all the modes of excitation are damped out in finite time, or they can be associated with the disappearance of complex patterns. Practically the relaxation time can be defined by the time span for stress to drop from its maximum at t_E to certain predefined level e.g. by the factor $^1/_e$,

$$A(t) = A(t_E)\exp(-t/t_R), \text{ then for } t = t_R$$
$$A(t_R) - A(t_E)/e$$

The relaxation length can then be defined by the spatial extent of seismic activity during the relaxation time.

The correlation length in terms of an equal time correlation function is:-

$$C(r_1 - r_2) = \left\langle (u(r_1, t) - \langle u \rangle)(u(r_2, t) - \langle u \rangle) \right\rangle$$

where <.........> denotes an average over *t,* and *u* (*r, t*) is some relevant local variable, e.g. stress, strain, frequency of occurrence etc. In many cases one will have $C(r) \sim \exp(-r/l_C)$, *as* $r \to \infty$, which then defines the correlation length l_c.

As long as $l_c > L$ we are dealing with a "small" system, which may be regular or chaotic in time but is coherent in space. If $l_c << L$, the dynamical behaviour is incoherent in space.

Application of the excitation, relaxation and correlation lengths holds great potential for discerning the seismic response to different mining procedures. Where seismicity is influenced by production blasting, these measures could be used to characterise sites or times where, for example, FULCO mining was done from those where it was not done. It does, however, require much higher seismic network sensitivity than is generally available on mines. Generally only a small number of events are recorded at each working place following production blasting - not enough to allow appropriate statistics.

3. Hazard criteria

3.1. Seismic Exposure

Seismic hazard derived from the size distribution of seismic events, i.e. the recurrence time, may not be adequate to quantify and to manage the exposure to seismicity, due to the difference in time of day distribution of intermediate and large events associated with different mining scenarios. It has been shown that stiffer systems are characterised by lower m_{max} but by the time of day distribution with larger statistical dispersion including multi-modality.

Seismic Exposure at a given site ΔV, averaged over the period Δt can be measured by the product of the average number of potentially damaging events at a given hour of day, $N(\geq m, h)/t$, and the average number of man hours, $mh(h)/\Delta t$ at that time of day

$$SE(\Delta V, \Delta t) = \frac{1}{\Delta t}\sum_{h=1}^{24} N(\geq m, h)\cdot mh(h)$$

The following example demonstrates the case.

3.1.1. Time of day method

The objective is to evaluate the seismic hazard of a particular shifting procedure. Through in depth empirical analysis of time of day distribution of personnel and seismic events, a number will be derived to express the seismic exposure rating (SE). By normalising this number to production figures it will then be possible to compare the difference in seismic safety of different shifting procedures performed on the same area.

3.1.1.1. Required Information:

- Cage schedule (including times of different personnel groups)
- Seismic data (must be sufficient to give an accurate account of daily frequency rates)
- Personnel counts of the different groups
- Production data (centares of the time period in question)

3.1.1.2. Procedure:

1. Inspect cage schedule and group counts to determine the time of day distribution of personnel in the stope areas (add travelling times where applicable). Repeat for total personnel in mine. The given example has been analysed with half-hour and one-hour increments with counts occurring on the quarter-hour and half-hour midpoints respectively.
2. Determine the frequency of events greater than magnitude one occurring in each increment of the day for the time period in question and divide this number by the number of days in that time period. This number is the expected frequency rate for events greater than or equal to magnitude one. Repeat for magnitude two.
3. Multiply the expected frequency rate of events greater than or equal to magnitude one with the number of people in the stopes at the respective time. Repeat for events greater than or equal to magnitude two.
4. Sum the products from the previous step for the entire day. This gives the 'daily SE'. Multiply this number by the number of production days during the period in question This number is SE. Divide SE by the centares mined to get a rating, which can be compared to other ratings of different scheduling on the area in question.

3.1.2. Results:

The method is applied in the case studies below (Chapter 4) - example results are given in Tables 4.1 and 4.2 and associated figures. Data was taken from a typical South African gold mine. Data comes from one year of 11-day Fortnight and one year of FULCO. Tables 4.1 and 4.2 give a quick summary of the number of people on each shift and the times at which these shifts are at different areas in the mine. Figures 4.1 to 4.4 give a visual indication of what SE is attempting to analyse (i.e. regions where both the bars and points are high, contribute to a high SE).

3.1.3. Discussion:

Although this method is quite laborious, it does allow for an in depth evaluation of seismic risk through the course of the day. It is important to restrict this type of analysis to data sets, which are sufficiently large that a proper measure of expected frequency rate be obtained. However, extremely large data sets should also be avoided so that data comes from similar conditions. Data sets from 6 to 12 months appear optimum.

There is a period shortly before blasting (14:00 in the given case) where seismicity increases considerably, while the cage scheduling suggests personnel is still in the stope. This early peak in seismicity may be attributed to early blasting and such personnel will have cleared the stopes. Because of the grouping of times into intervals the accuracy of cage and seismicity timing is lost. That is, most of the events associated with early blasting may have occurred just minutes before 14:00, when all personnel have been cleared from the mine. However, because these events fall into the before 14:00 bin, they are grouped into a time slot which has a considerable number of people in the mine rather than none at all. This effectively increases the SE for this time period and contributes considerably to the daily SE. For the same reason, choice of bin size is also critical to the determination of SE. In the given example, the larger bin size yields a larger daily SE. To avoid such inflation in evaluating SE, the number of people in the mine during the time period in question is set to zero.

When comparing FULCO to 11-day fortnight operations, one could normalise SE to production for comparison purposes. It is also important to make comparisons between areas of similar (geology, etc.) description because these parameters all contribute to seismic response. To allow fair comparisons, areas that have been mined using FULCO and a more traditional scheduling procedure, for sufficient lengths of time, are required. The availability of such databases was, however, found to be limited.

The procedure of counting events above a given magnitude presents a particular limitation. If, for example, the events above magnitude 2.0 are counted, the important hazard resulting from a possible large number of events of magnitude 1.9 is ignored. This artefact reduces as the magnitude of choice reduces, but then the possibly non-hazardous small events dominate.

In order to compensate for the fact that the personnel will experience different exposure with different scheduling procedures, the hourly SE must be multiplied by the number of production days in the time in question. For an example, FULCO scheduling could result in 352 production days per annum (365 – 13 public holidays), whereas eleven-day fortnight scheduling could result in 274 production days (352 – 52 Sundays – 26 Saturdays).

3.2. The problem of larger events

3.2.1. General

The basis for SE is a traditional way of quantifying seismic hazard, namely ' the number of events greater than magnitude X'. It can easily be shown that, for overall hazard assessment, this way of counting the number of events above some arbitrary cut-off is inadequate. If, for example, the cut-off chosen is magnitude 2.0, events of magnitude 1.9, which can cause fatal accidents, are not counted. Furthermore, the number of events > 2 may or may not include events of say magnitude > 3.5. Such larger events dominate the seismic hazard and their presence may be hidden by the counting method.

Another way is to express the seismic hazard in terms of the sum of seismic energy released. Although intuitively this may appear to be the most robust measure of seismic hazard, it is difficult to compare the seismic hazard between two different areas or time spans when a small number of very large events are included in the data sets. This is because of the fact that seismicity is intermittent is space and time. The inclusion or not of a large event in a population can depend on minutes in time or metres in space. This becomes a serious problem when such large event completely dominates the seismic hazard assessment parameter (e.g. sum of radiated seismic energy). One way to overcome this problem for larger data sets is to do Gutenberg-Richter statistics. The statistical fit causes smoothing and the *a* and *b* values are not highly sensitive to the occurrence or otherwise of one large event. This approach works well for large data sets and can be further sophisticated by linking to the E-M statistics and quantifying a statistically based strong ground motion hazard assessment (e.g. *van Aswegen et al., 2000*). For the small data sets found in particular hours of day in one year for one mine, this approach is, however, not applicable.

The 'number of events > X method entrenched in the SE procedures can be defended specifically with reference to the larger events. We note that, although a specific combination of rockmass- and loading system stiffness and rockmass rheology can cause a specific preferential time of day occurrence of larger events away from blasting, it is generally true that the larger the event, the more random the time of day distribution (e.g. *van Aswegen, 2000*). If there is indeed an increased frequency of larger events at a specific time of day, one would generally expect an increase in the frequency of all events during such time and the phenomenon will be reflected in the SE analysis. Because of the randomness of the largest events, it would not be fair to use a quantitative hazard assessment such as the sum of radiated seismic energy, to compare the time of day hazard. The coincidental occurrence of one large event at any particular hour will distort the hazard assessment significantly. Since the true probability of occurrence of such large events could be considered random in terms of time of day, the hazard contribution of such events should, in fact, be evenly spread over all hours of day. The problem now arises as to what the lower magnitude cut-off of such 'random' events should be. The problem can, in fact, not be solved by event magnitude cut-offs. Rather, sophisticated statistical techniques would be required to fairly distribute the time of day hazard contribution of intermediate events.

If we consider further the fact that the majority of fatal seismicity related rock fall and rockburst accidents are associated with events between magnitude 1 and 2.5 then the 'number of events above magnitude 1' criterion turns out not such a bad hazard assessment parameter.

3.2.2. Method for prorating events

One attempt to pro-rate all events to equivalent magnitude 1 events is described here. The idea is to translate say 10 magnitude 0 events into 1 magnitude 1 event, while 1 magnitude 2 event will count as 10 magnitude 1 events (the multiplication factor being a function of the b-value).

The method of prorating events makes use of the *b*-slope of the Gutenberg-Richter relation to rate events, based on their magnitudes, to an equivalent number of events equal to magnitude 1.0. The formula is given as:

$$N_o = 10^{b(m-1)}$$

Where N_o is the equivalent number of events equal to magnitude 1.0,
b is the slope of the Gutenberg-Richter relation and

m is the magnitude of the event.

To illustrate using some examples, consider a *b*-slope of 0.94 and two events, one of magnitude 0.5 and one of 3.0. The first event magnitude has a prorating (N_o) of 0.339. The second has a N_o of 100. Clearly the larger events are favoured. In principle, given enough time, the numbers should balance since few large and many small events will occur.

This method results in a higher number for events equivalent to magnitude 1.0. Peaks in seismicity resulting from blasting may not be as prominent because larger events, occurring at different times in the day, are favoured. Because the prorated method accounts for all events > 0.0 and each of the larger events count for more than one, the SE is considerably higher for the same data set.

Depicted in Figure 3.1 is the Gutenberg Richter plot, from which the *b*-slope (0.78) is taken and used in the equation to prorate events

Figure 3.2 shows the results of using the method of counting events > magnitude 1.0 and Figure 3.3 reflect the results using the method of prorating all events >0.0 magnitude to equivalent magnitude 1.0 events. The results are tabulated in Table 3.1, showing a much higher SE rating for the case where prorating is applied as opposed the case where it is not. Note the higher SE for the 7th when the method of prorating is applied. This is due to two large events occurring during that time of day. Note also, the smaller scale on the vertical axis (of Figure 3.3) for the frequency rate.

Table 3.1. The effect of prorating on the value of SE

	Daily SE	SE/centare
SE normal	112.93	0.203
SE on prorated events	343.33	0.618

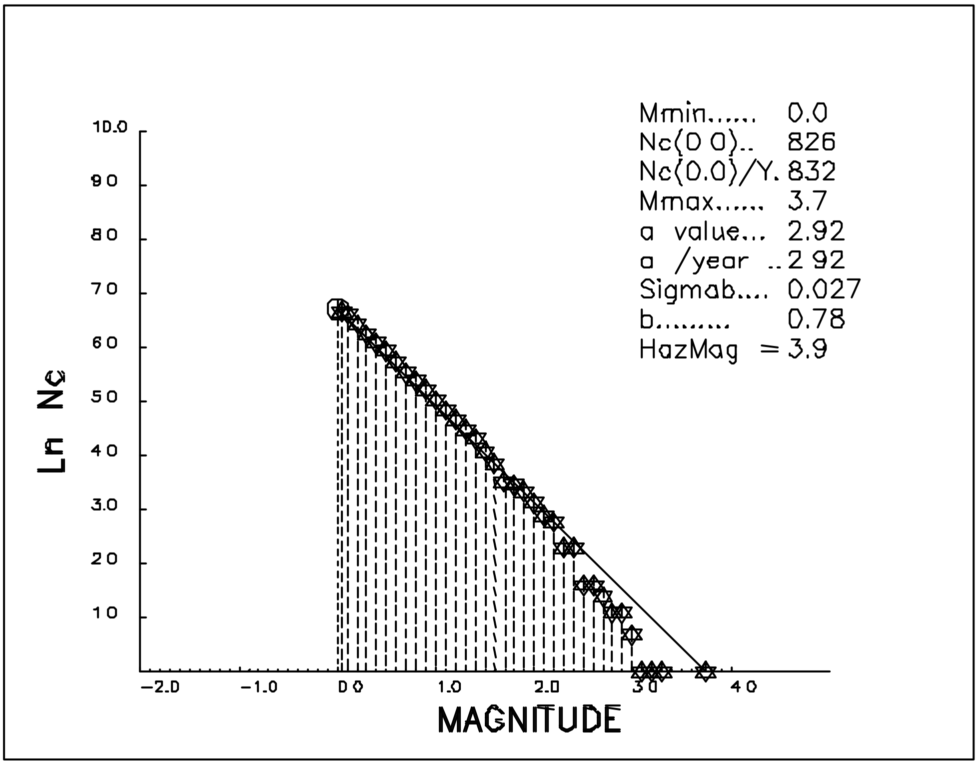

Figure 3.1. Gutenberg Richter plot of 11-day fortnight data.

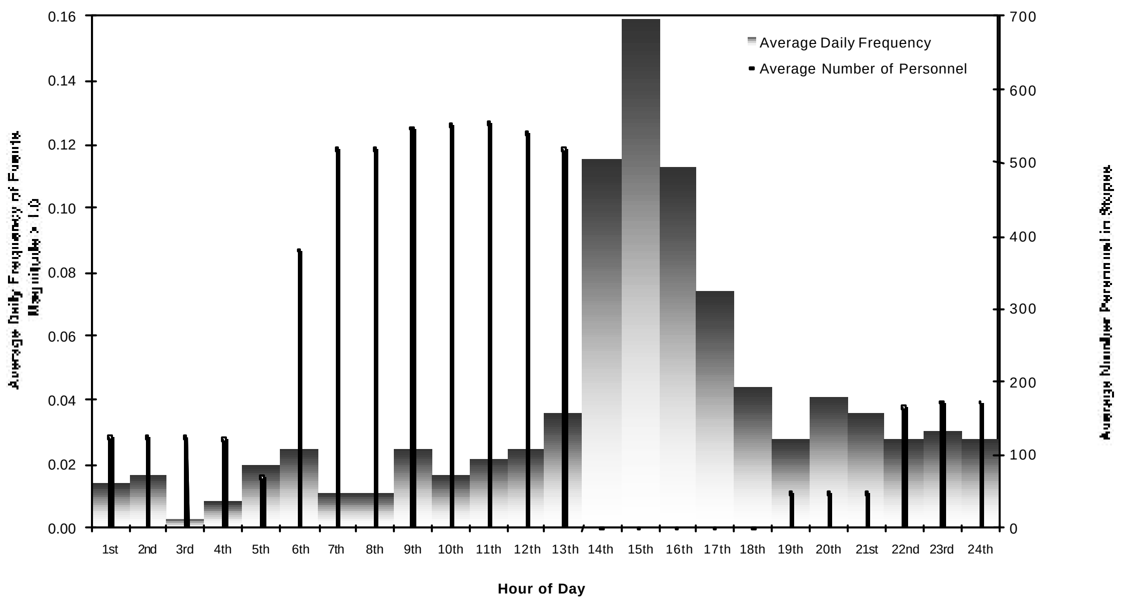

Figure 3.2. Personnel in Stopes and Event Frequency >1.0 for Time of Day Distributions for 11-day Fortnight. The event frequency is normalised by the total number of days of observation – see 3.1.1.2

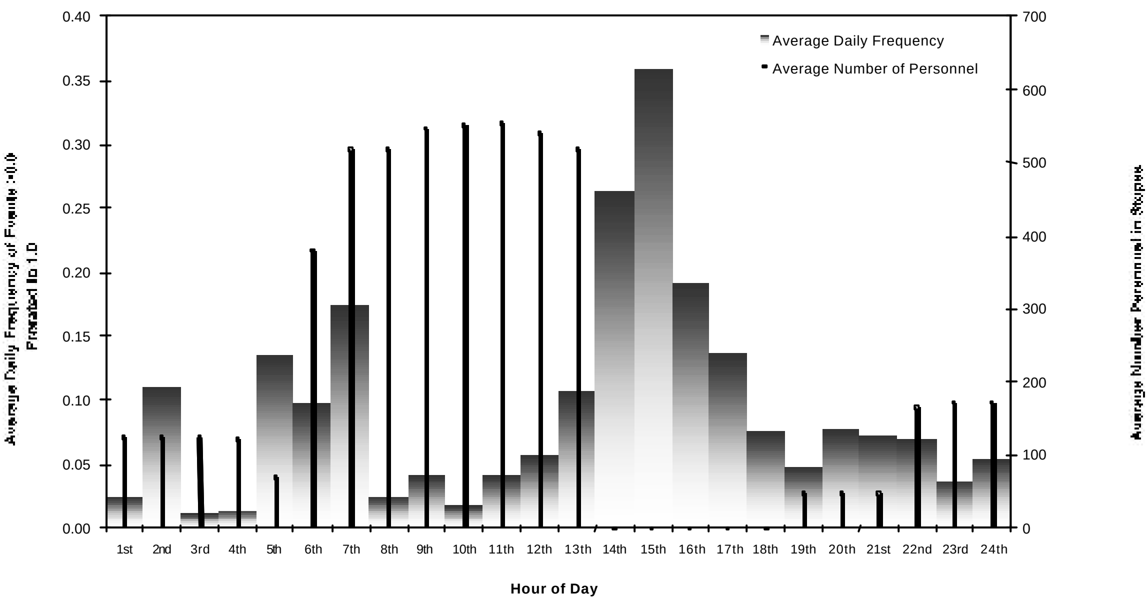

Figure 3.3. Personnel in Stopes and Frequency of Events >0.0 Prorated to 1.0 for Time of Day Distributions for 11-day Fortnight Operations

The same problem as with the quantitative hazard assessment arises, however - one magnitude 4 event will significantly distort the SE by being pro-rated to say 1000 magnitude 1 events. The conclusion is thus that the standard procedure for the calculation of SE, as described above, without the pro-rating, is the most objective way. Since the largest events do occur most randomly in time, they should not contribute to the SE by pro-rating. Their contribution is seen in the overall hazard. Comparing two mining methods, one should consider the overall hazard as well as the SE.

3.3. Gutenberg-Richter and Energy-Moment analysis

The slope of the Gutenberg-Richter Plot (referred to as the *b*-value) can be interpreted as a measure of the stiffness of the loading system. Loading system stiffness is an important parameter in determining seismic hazard. A steep *b*-slope (indicating a high loading system stiffness) is considered as favourable because it results in a lower maximum magnitude (refer to GAP303 pages 15-17). A steep slope may indicate a greater number of lower magnitude events (depending on the corresponding *a*-value) but the mine support system would be more likely to withstand such events. A stiff system also, however, has its drawbacks from a seismic safety point of view. Stiffer systems are often more variable in their time of day distributions. Softer systems experience a greater proportion of events within the hours just after blasting. These events pose limited threat to safety as the workers have, during this time, evacuated the mine. Stiff systems mean longer relaxation periods and relaxation times, increasing the probability of larger events to occur on shift.

The slope of the E-M relation also correlates with stiffness. The convention proposed in the Guide to Routine Seismic Monitoring in Mines (*Mendecki et al., 1999*) is being followed, referring to the slope and intercept of the Energy Moment (E-M) relation as the *d*- and *c*- values. The *d*-value, increases with increasing system stiffness. Just as the relation of the Gutenberg-Richter plot is subject to the translation of the *a*-value, so is the E-M relation subject to the translation of the *c*-value. When the *d*-slope of a system is held constant, the *c*-value is effectively a measure of stress. A steeper *d*-slope has particular implications in seismic hazard. A stiff system releases energy at a greater rate with increase in moment (i.e. for the same moment, stress drop will be higher in a stiffer system). High stress drop events are more violent and thus potentially more dangerous to workers underground. Coupled with the time of day variation of event distribution this may have consequences with regard to seismic safety. More importantly however, in stiffer systems the maximum magnitude is restricted (GAP303).

4. Case Studies

4.1. Case study A

The following analyses were done for a mine in the West Wits area. Data is taken from one year of 11-day fortnight operations just prior to FULCO and one year of FULCO immediately following its introduction. It should be noted that, although the scheduling change occurred mine-wide, the mining strategy also changed coincident with the advent of FULCO. Concentrating on the mining of high-grade areas, the mine achieved its gold production requirements through lower total centares mined.

4.1.1. Seismic exposure analysis

Table 4.1 contains time of day distributions of personnel and seismic events with magnitudes >1.0 11-day fortnight operations. The data is graphically illustrated in Figure 4.1 while Figure 4.2 shows the time of day distribution of events > mag. 2.0. Note that when the frequency/number is high for both events and personnel, the SE is also high. When viewing the figures 'potential problem times' for the >1.0 magnitude events are easily discerned, such as the 6^{th}, 9^{th} and 11^{th} to 13^{th} hours. Moderate contributions to SE also come from the 22^{nd} to 24^{th} hours. For the events with magnitude >2.0, a large contribution to SE will come from the 13^{th} hour, with moderate hourly SE coming from the 6^{th}, 8^{th}, 9^{th}, 12^{th} and 22^{nd} hours.

Table 4.2 contains the same information as Table 4.1 but for FULCO operations. Figures 4.3 and 4.4 are plots of this data. Maximum 'Potential problem times' are the 9^{th} and 13^{th} hours for both magnitudes, with the 11^{th} and 12^{th} hours also important.

Daily SE numbers, shown in Table 4.3, actually decrease with the advent of FULCO, suggesting that the time of day distribution hazard actually improved. However, because there are more days in the year when people are exposed to the hazard, SE must be corrected for this by multiplying daily SE by the number of production days. For FULCO this ratio is much higher. The SE may also be normalised to production (divided by the total centares removed). In this case, FULCO operations resulted in a lower centares achieved (the mining was more concentrated due to high grading). Therefore, there are two factors that pushed the SE/centare higher for FULCO from a lower daily SE rating:

- The ratio of production to total days was higher for FULCO.
- The total number of centares achieved was lower for FULCO.

These calculations can be followed through in Table 4.3.

Table 4.1. SE calcualtions for Case A, 11-day fortnight.

Hour of Day	Frequency of Events >1.0 mag.	Average Daily Frequency of >1.0	Personnel in Stopes During Production	Hourly SE	Events >0.0 Prorated to 1.0	age Daily Fre .0 Prorated	Hourly SE
1st	5	0.0183	165	3.02	7.5	0.0275	4.53
2nd	6	0.0220	165	3.63	89.14	0.3265	53.88
3rd	1	0.0037	165	0.60	2.63	0.0096	1.59
4th	3	0.0110	162	1.78	3.35	0.0123	1.99
5th	7	0.0256	93	2.38	122.11	0.4473	41.60
6th	9	0.0330	507	16.71	66.44	0.2434	123.39
7th	4	0.0147	694	10.17	4.18	0.0153	10.63
8th	4	0.0147	694	10.17	10.42	0.0382	26.49
9th	9	0.0330	731	24.10	17.06	0.0625	45.68
10th	6	0.0220	736	16.18	5.28	0.0193	14.23
11th	8	0.0293	739	21.66	16.52	0.0605	44.72
12th	9	0.0330	722	23.80	30.16	0.1105	79.76
13th	13	0.0476	694	33.05	54.45	0.1995	138.42
14th	42	0.1538	0	0.00	137.38	0.5032	0.00
15th	58	0.2125	0	0.00	178.25	0.6529	0.00
16th	41	0.1502	0	0.00	67.05	0.2456	0.00
17th	27	0.0989	0	0.00	51.7	0.1894	0.00
18th	16	0.0586	0	0.00	31.13	0.1140	0.00
19th	10	0.0366	64	2.34	20.53	0.0752	4.81
20th	15	0.0549	64	3.52	36.54	0.1338	8.57
21st	13	0.0476	64	3.05	33.64	0.1232	7.89
22nd	10	0.0366	221	8.10	33.38	0.1223	27.02
23rd	11	0.0403	229	9.23	13.68	0.0501	11.48
24th	10	0.0366	229	8.39	24	0.0879	20.13
Daily Totals:				201.87			666.80
			Number of Production Days:		273		
			Total Number of Days:		365		

Table 4.2. SE calculations for Case A, FULCO.

Hour of Day	Frequency >1.0 per Year	Average Daily Frequency of >1.0	Workers in Stopes During Production	Hourly SE	Events >0.0 Prorated to 1.0	age Daily Fre .0 Prorated	Hourly SE
1st	3	0.0110	165	1.81	3.07	0.0112	1.86
2nd	6	0.0220	165	3.63	18.41	0.0674	11.13
3rd	6	0.0220	165	3.63	5.43	0.0199	3.28
4th	3	0.0110	162	1.78	9.83	0.0360	5.83
5th	5	0.0183	93	1.70	10.35	0.0379	3.53
6th	4	0.0147	507	7.43	7.88	0.0289	14.63
7th	3	0.0110	694	7.63	18.66	0.0684	47.44
8th	2	0.0073	694	5.08	3.21	0.0118	8.16
9th	9	0.0330	731	24.10	325.26	1.1914	870.93
10th	2	0.0073	736	5.39	3.32	0.0122	8.95
11th	5	0.0183	739	13.53	82.22	0.3012	222.57
12th	4	0.0147	722	10.58	4.11	0.0151	10.87
13th	10	0.0366	694	25.42	16.47	0.0603	41.87
14th	26	0.0952	0	0.00	48.43	0.1774	0.00
15th	41	0.1502	0	0.00	130.61	0.4784	0.00
16th	28	0.1026	0	0.00	42.03	0.1540	0.00
17th	26	0.0952	0	0.00	50.55	0.1852	0.00
18th	11	0.0403	0	0.00	38	0.1392	0.00
19th	9	0.0330	64	2.11	47.79	0.1751	11.20
20th	15	0.0549	64	3.52	60.24	0.2207	14.12
21st	4	0.0147	64	0.94	50.66	0.1856	11.88
22nd	5	0.0183	221	4.05	36.03	0.1320	29.17
23rd	5	0.0183	229	4.19	4.86	0.0178	4.08
24th	8	0.0293	229	6.71	11.9	0.0436	9.98
Daily Totals:				133.23			1331.47
			Number of Production Days:		349		
			Total Number of Days:		365		

Table 4.3. Summary of the SE calculations for Case A.

	11-day Fortnight	**FULLCO**
SE/day	201.87	133.23
N prod. Days	273	349
Centares produced	202712	153129
SE/centare	0.2719	0.3036

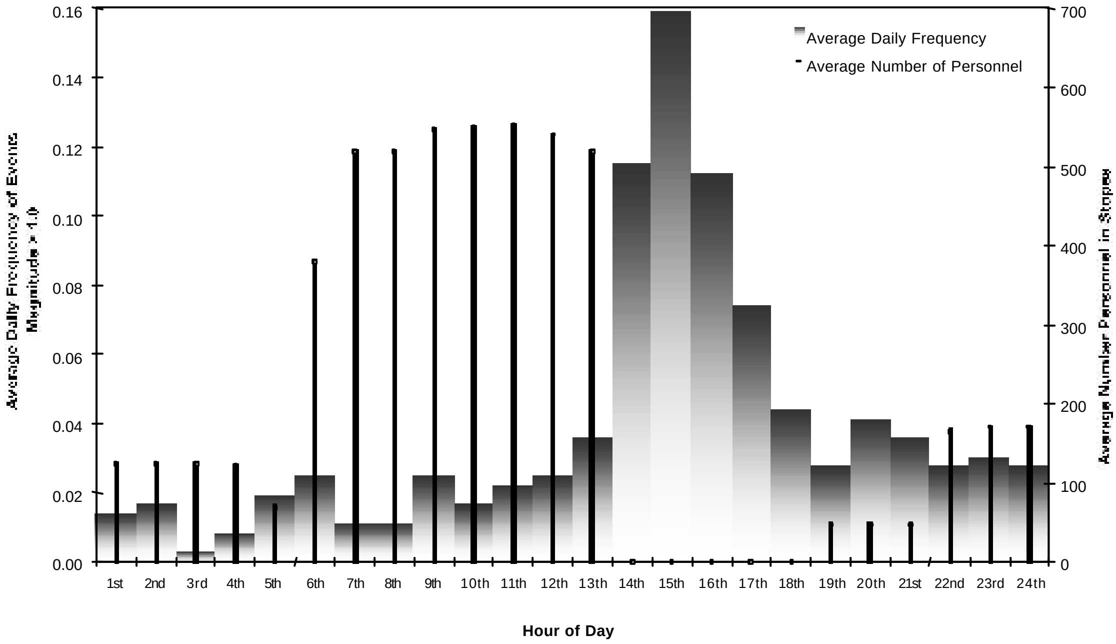

Figure 4.1. Personnel in Stopes and Event Frequency > 1.0 Time of Day Distributions for 11-day Fortnight.

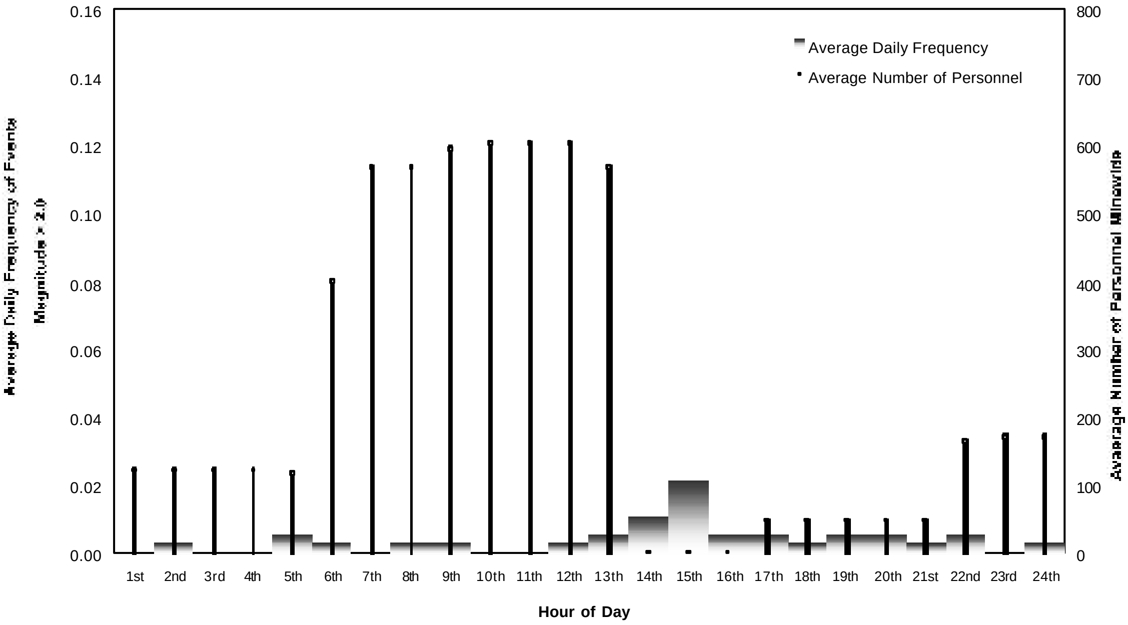

Figure 4.2. Personnel Underground and Event Frequency >2.0 Time of Day Distributions for 11-day Fortnight.

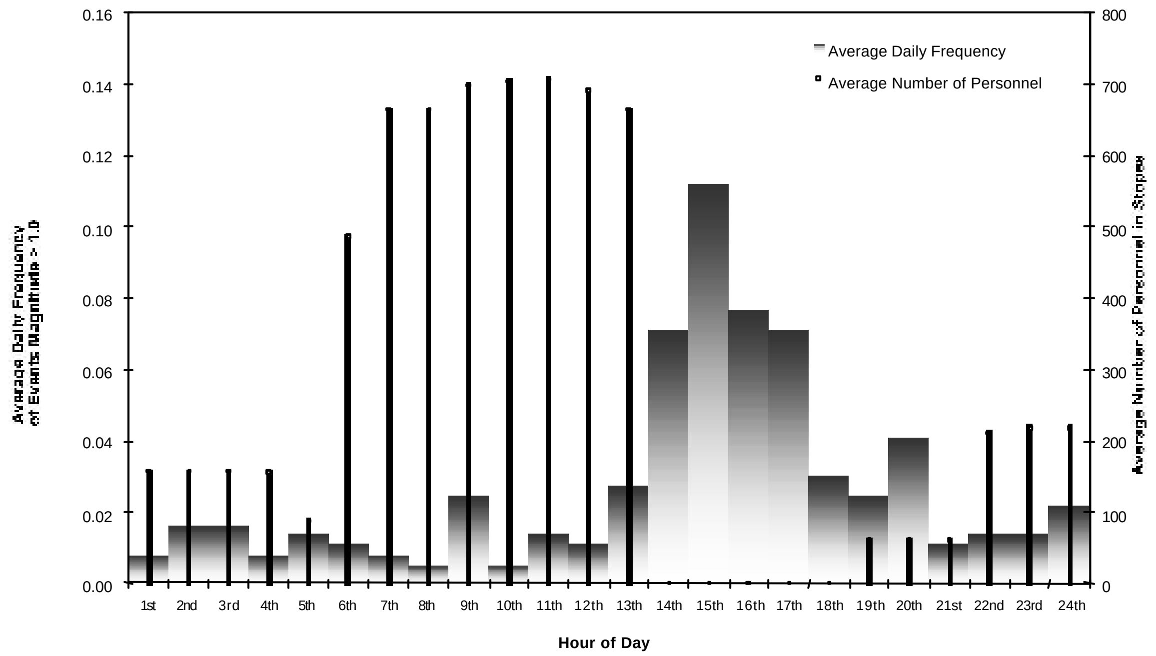

Figure 4.3. Personnel in Stopes and Event Frequency >1.0 Time of Day Distributions for FULCO.

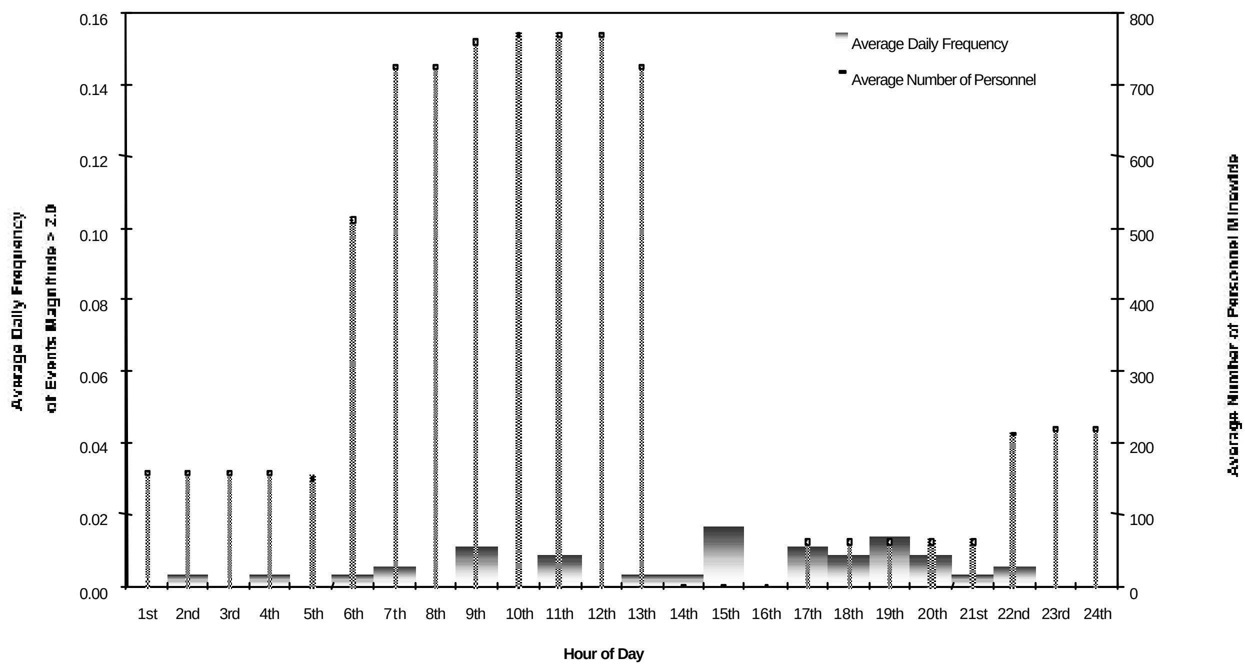

Figure 4.4. Personnel Underground and Event Frequency >2.0 Time of Day Distributions for FULCO.

4.1.2. Gutenberg-Richter and Energy-Moment analysis

4.1.2.1. The different event size populations

The test of the general rockmass response to the different mining schedules can be quantified by the G-R and E-M statistics.

Figure 4.5 shows two Gutenberg-Richter plots (local magnitude), one using data from the year of FULCO and one using data from the preceding year of 11-day Fortnight operations. Note that, in both cases, the size distribution defines three event size populations:
Population 1: Events < mag. –0.5, defining a steep *b*-slope,
Population 2: Events > mag. –0.5 and < mag. 2.0, defining a shallow *b*-slope, and
Population 3: Events > mag. 2.0 defining a steeper *b*-slope.

In these plots, the line fitting is by Aki's method (see *Mendecki et al, 1999*) with m_{min} at 2.0. This is done in an attempt to define the hazard associated with population 3 (i.e. the larger events). Although the event size at which to separate population 2 from population 3 is not clearly defined, using the same m_{min} value of 2.0 for both cases and then applying the objective Aki method for finding *b* should yield a fair comparison. The analysis yields a hazard magnitude of the same size, 3.6. The *b*-slopes (1.29 and 1.34) differ by 0.05.

Figures 4.6 and 4.7 are also Gutenberg-Richter plots for the 11-day fortnight and FULCO periods, but using the Hanks Kanamori Moment magnitude relation and the Gibowicz energy-magnitude relations respectively. The focus is on population 3. The moment magnitude plots shows the same change in *b*-value for the larger events as the local magnitude plots. The plot using the Gibowicz Energy Magnitude, produces a *b*-slope for the FULCO data that is slightly lower. Closer inspection of the graphs, however, reveal that, for the most part of the particular subset of data of interest here, the b-slope is indistinguishable (the thicker, red line on both plots have identical slopes).

Representative E-M statistics for the larger events (shown in Fig's. 4.12 and 4.13 below) yield a steeper *d*-slope for the FULCO data also suggesting that this scheduling induced a stiffer system.

Analyses were also conducted on population 2. Figures 4.8 and 4.9 are Gutenberg-Richter plots using robust line fitting for the second population (local magnitude and moment magnitude. respectively). The data used ranges from magnitude –0.5 (m_{min}) to 2.0 (local magnitude). The *b*-slope of the lines, 0.71 and 0.65 for 11-day fortnight and FULCO respectively, indicate that, for this population, 11-day fortnight operations induced a stiffer system. The same trend is observed for the moment magnitude plot where the *b*-slope changes from 0.94 to 0.85. These *b*-slopes also suggest that population 2 reacted stiffer during the 11-day fortnight operations.

Figures 4.10and 4.11 are plots using the E-M relation for population 2. The *d*-slopes are 1.22 and 1.17 for 11-day fortnight and FULCO respectively. The difference between these two slopes is considerably less than that found in the third population, but it remains significant and suggests a stiffer system under 11-day fortnight operations.

Table 4.4 summarises the results of the analysis.

Table 4.4. Summary of Gutenberg-Richter and Energy-Moment Analyses for Case Study A

Analysis	Results	Inference
Gutenberg-Richter using Mine Parameters – population 3	***b*-slope:** 11-day fortnight < FULCO	FULCO mining induces a stiffer system for population 3
Gutenberg-Richter using Hanks Kanamori Moment Parameters – population 3	***b*-slope:** 11-day fortnight < FULCO	FULCO mining induces a stiffer system for population 3
Gutenberg-Richter using Gibowicz's Energy Parameters – population 3	***b*-slope:** 11-day fortnight = FULCO	FULCO mining induces no change for population 3
Energy-Moment Relation – Larger events	***d*-slope:** 11-day fortnight < FULCO	FULCO mining induces a stiffer system for population 3
Gutenberg-Richter using Mine Parameters – population 2	***b*-slope:** 11-day fortnight > FULCO	11-day fortnight mining induces a stiffer system for population 2
Gutenberg-Richter using Hanks Kanamori Moment Parameters – population 2	***b*-slope:** 11-day fortnight > FULCO	11-day fortnight mining induces a stiffer system for population 2
Gutenberg-Richter using Gibowicz's Energy Parameters – population 2	***b*-slope:** 11-day fortnight > FULCO	11-day fortnight mining induces a stiffer system for population 2
Energy-Moment Relation – Population 2	***d*-slope:** 11-day fortnight > FULCO	11-day fortnight mining induces a stiffer system for population 2

As shown in Table 4.4 there is a significant and consistent change in the G-R and E-M statistics between 11-day fortnight operations and FULCO. In the case of the larger events the *b*- and *d*-values increase, while for the small to intermediate events the opposite is true, i.e. the *d*- and *b*-values decrease. Although these changes did not change the bottom line seismic hazard (see below) some **speculation** on the reason for these particular statistical patterns is given below.

Changes in *d*- and *b*-values can generally be attributed to changes in system stiffness (see GAP303). The differences shown here are complicated by the fact that the system stiffness appears to increase for the larger events and decrease for the small to intermediate ones. The explanation may lie in the change from normal production to the concentration on high-grade areas that coincided with the change from 11-day fortnight operations to FULCO. The change could therefore also be towards 'scattered' mining and away from longwall mining. In such a case, the stress concentration usually found along long longwall faces would be lessened, causing a lower rate of loading on that sub-system producing the small to intermediate events (the joints and small structures which yield ahead of the mining face). The overall scattered nature of mining does also, however, cause a relative stiffening of the macro-system that controls the yielding of the larger events along the larger structures.

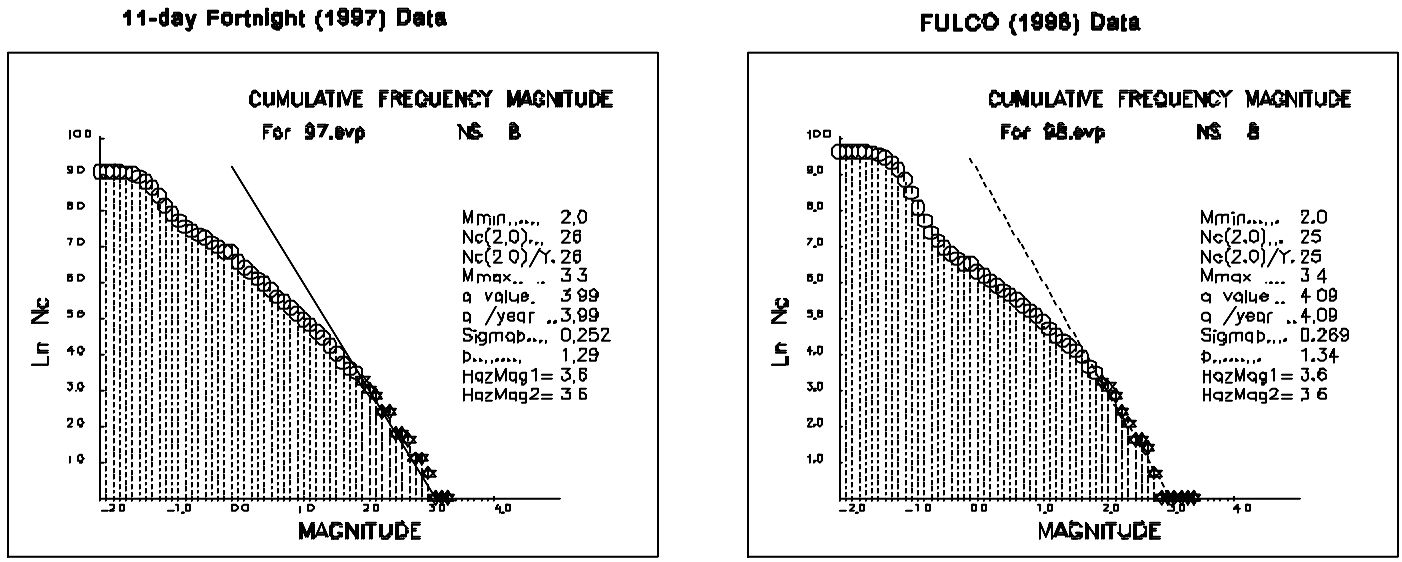

Figure 4.5. Gutenberg-Richter plot using local mine magnitude (based on energy and moment) for case study A. The b-slope determined through Aki's method.

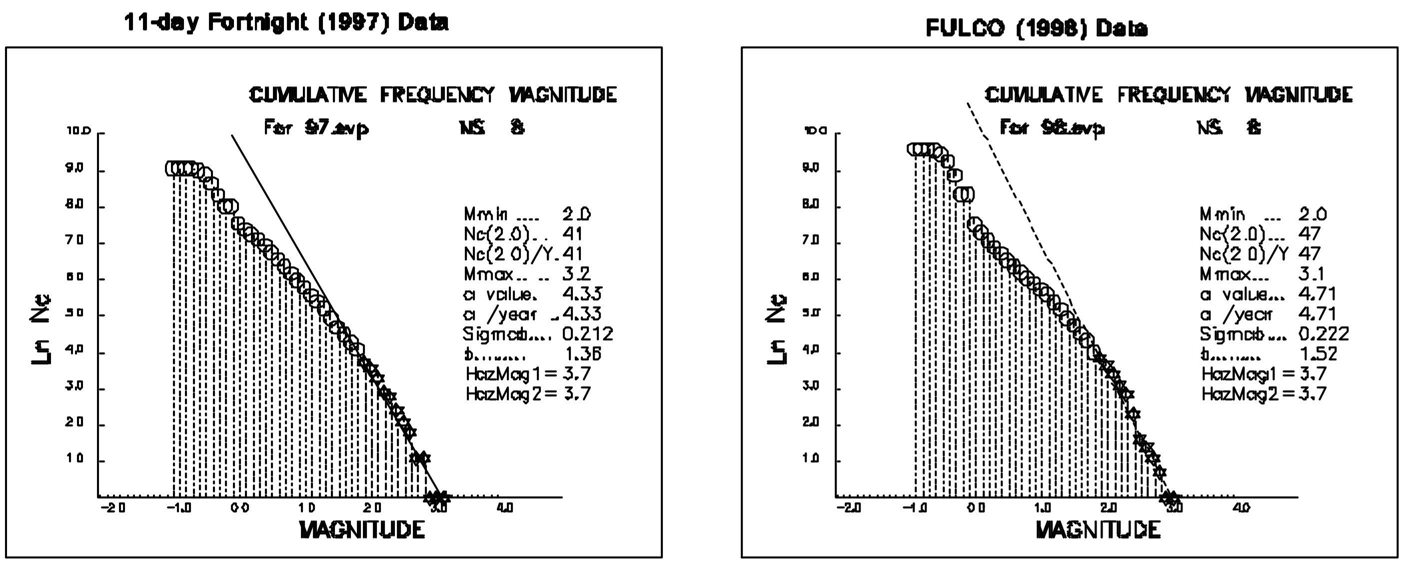

Figure 4.6. Gutenberg-Richter plot using Moment Magnitude, the line fitting based on Population 3.

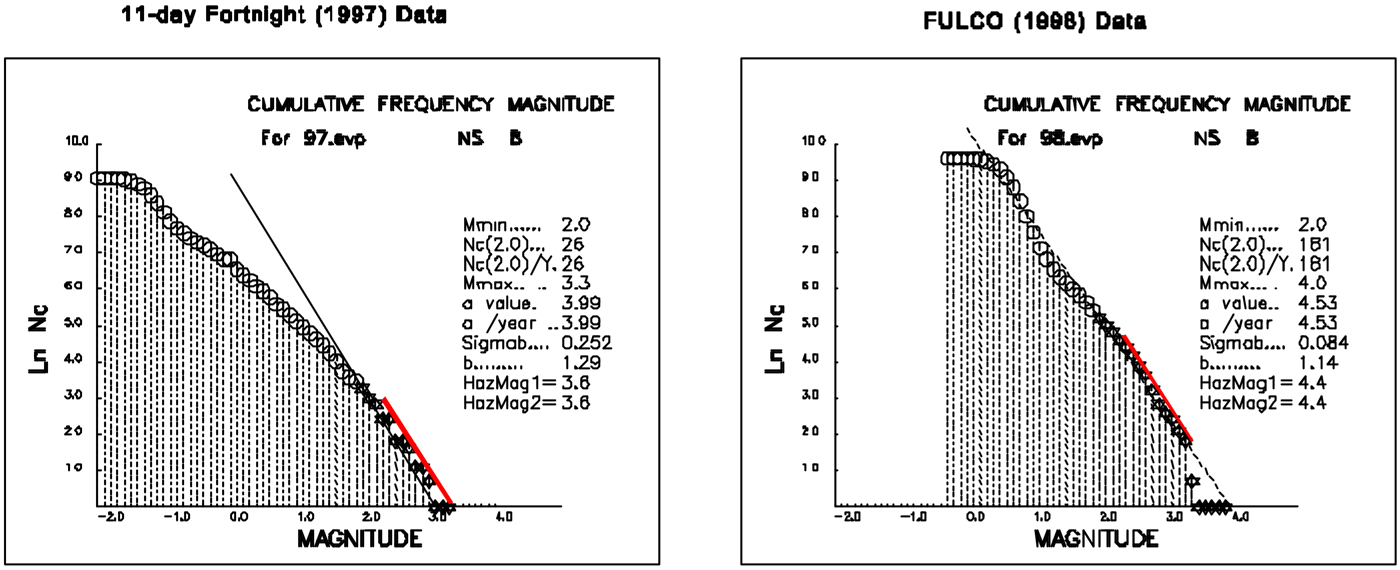

Figure 4.7. Gutenberg-Richter plots using Energy Magnitude, for Population 3.

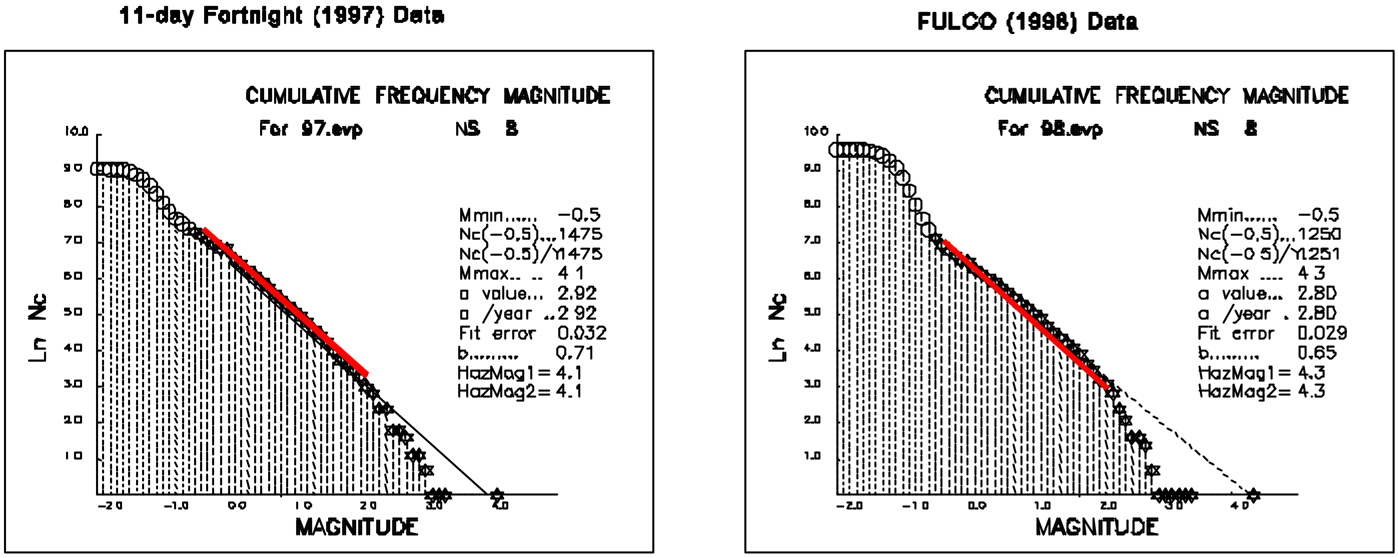

Figure 4.8. Gutenberg-Richter plot using local magnitude, on Population 2.

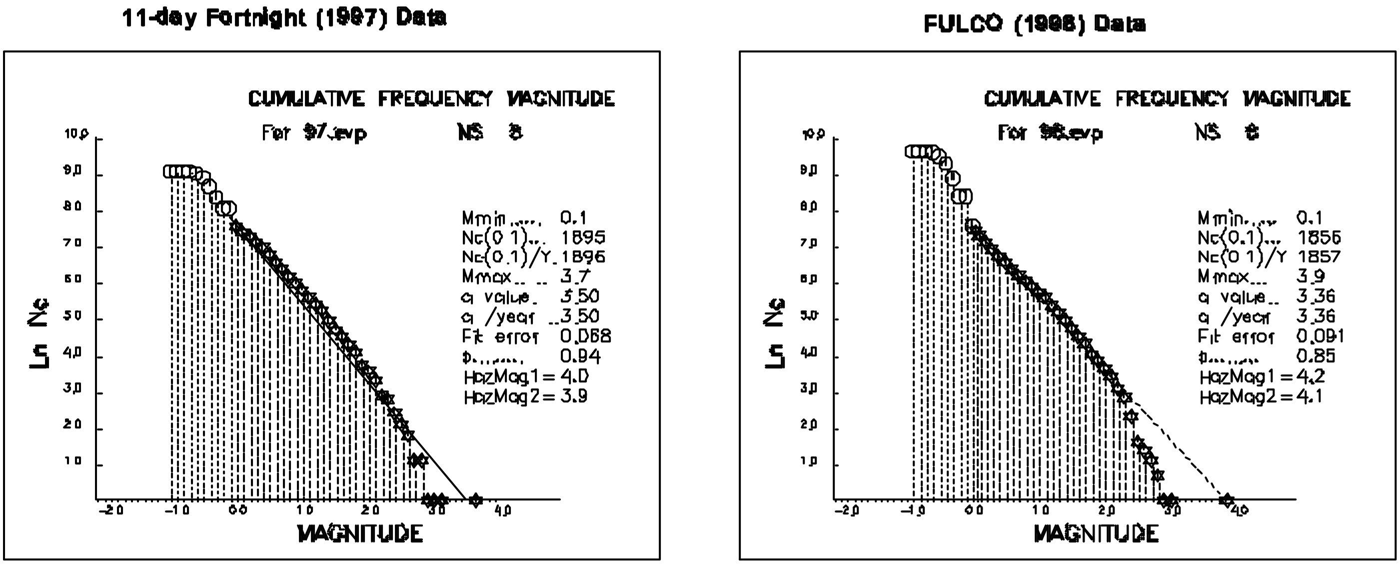

Figure 4.9. Gutenberg Richter plots using Moment Magnitude, on Population 2.

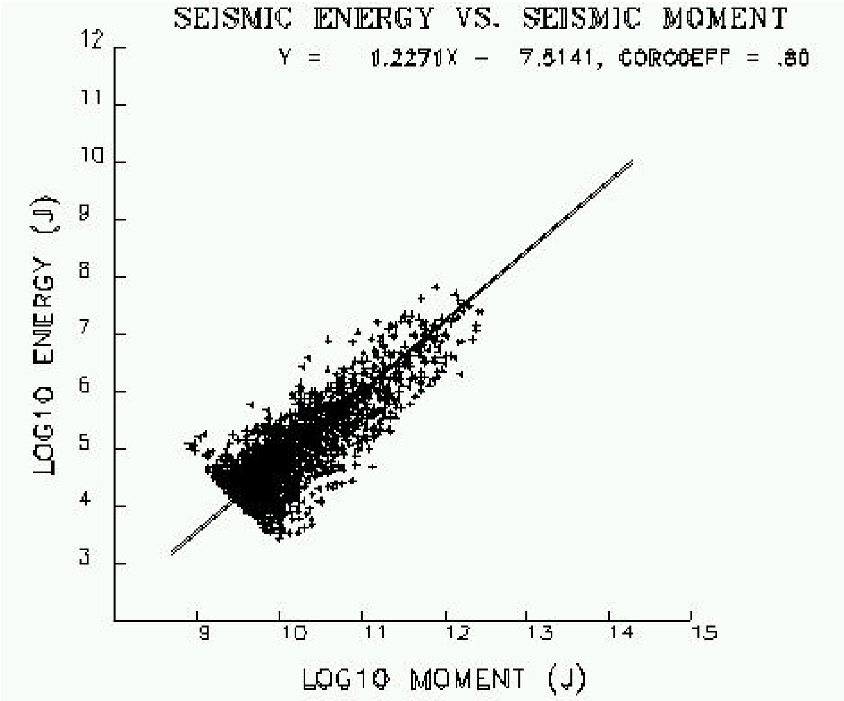

Figure 4.10. Seismic Energy vs Seismic Moment, for Population 2, 11 DFNT, Case A

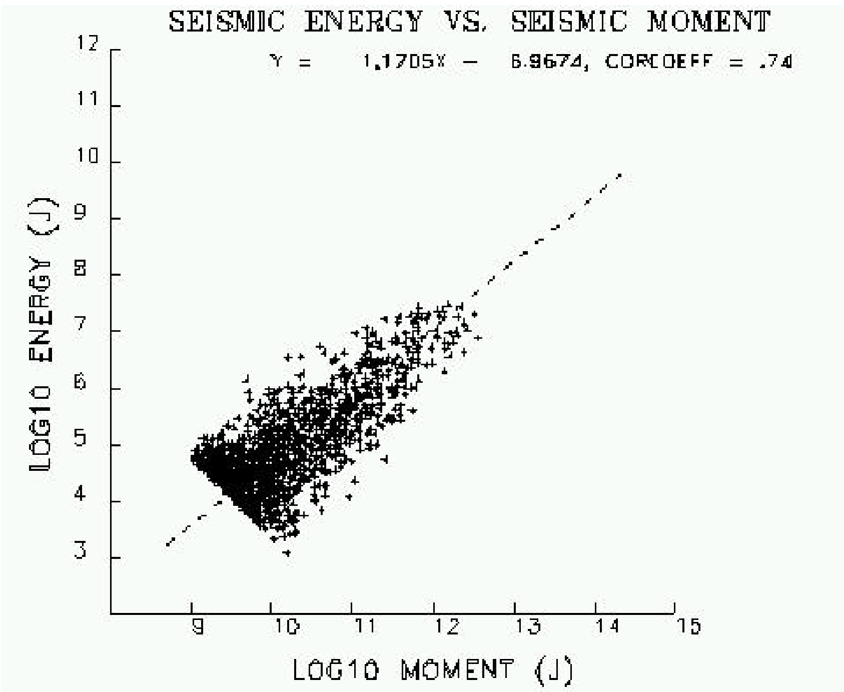

Figure 4.11. Seismic Energy vs Seismic Moment, for Population 2, FULCO, Case A

4.1.2.2. The general seismic hazard

The general seismic hazard for the two event data sets (FULCO and 11DFNT) can be established through traditional seismic hazard assessment procedures and also by applying somewhat more sophisticated procedures which include strong ground motion hazard assessment. These methods are based on statistical analyses and the effects of individual large events are, to a large extent, suppressed. In this section the general seismic hazard for the two periods of mining operations is presented and a comparison is made between the statistically defined and the observed hazard.

The standard hazard analyses outcomes are shown in Figure's 4.14 and 4.15 tabulated in Tables 4.6 and 4.7 and summarised in Table 4.5. Figs. 4.14 and 4.15 are standard Gutenberg-Richter plots based on the local magnitude. The slight differences to the parameter outcomes to that in Figure 4.5 stem from changing m_{min} from 2.0 to 1.8. The assumption here is that real seismic hazard may be limited to the larger events (one could argue that, if support standards and safety procedures are up to standard, very few accidents should result from smaller events). The 'PDR' in the figures stand for Potential Damage Radius. This is the radius of the PDA, which is an estimate of the area that was subjected to potentially damaging ground shaking due to seismic events. It depends on both the Gutenberg-Richter- as well as the E-M statistics. (see *van Aswegen, 2000*).

From Tables 4.6 and 4.7 one can read off different seismic hazard parameters, e.g. that the probability for an event > mag. 3 to occur in one year was 60% during 11-day fortnight operations and 35 % during FULCO. Similarly the likelihood of and event > mag 2.5 within one month decreased from 38% to 33 %. The integrated hazard parameters, namely Hazard Magnitude and PDA show very little change.

The E-M relations are shown in Figs. 4.13 and 4.14. The E-M statistics (summarised here in Table 4.5) show a decrease in Apparent Stress Level, but an increase in Apparent Stiffness. This is significant, since Apparent Stiffness normally increases with Apparent Stress Level (because, as a result of the particular definition of Apparent Stiffness, it will increase if the *d*-value remains constant and the *a*-value increases - see Glossary of Seismological Terms, GAP303).

Table 4.5. Summary of Gutenberg-Richter and E-M statistics for Case A 11-day + FULCO

	d-slope	c_value	corr.	Ap.Stiff[MPa]	App.Str.L[KPa]	c_app
A_11DF	1.29079	-8.33627	0.80760	26.38000	469.46000	-8.98777
A-FULCO	1.39140	-9.56486	0.74600	31.67000	381.70000	-9.07764
	b-val	**Mmin**	**Mmax**	**Hazmag**	**PDA-from G-R**	**PDR from G-R**
A_11DF	1.07	1.80	3.26	3.71	1694	23
A-FULCO	1.19	1.80	3.12	3.70	1794	23
	N-events>1	**PDA from data**	**PDR from data**			
A_11DF	548	634	14			
A-FULCO	421	973	18			
A_11DF	547	600	14	without observed Mmax		
A-FULCO	420	532	13	without observed Mmax		

The change in E-M statistics thus also indicate lower hazard during FULCO. The higher stiffness does, however, reflect relatively higher strong ground motions and the higher *d*-value is seen by the analysis procedure as reflecting a higher number of small events. Since the cut-off for the integrated hazard parameters is mag. 1, the generally lower hazard during FULCO for events above mag. 1.8, as indicated by the G-R statistics, is compensated for by an inferred (not actual) greater hazard between mag. 1 and 1.8, thus causing the integrated hazard parameters to be similar.

Except for the one largest event that occurred during FULCO, the observed hazard was, in deed, lower during this period of mining. To illustrate the effect of one large event, a quantitative seismic hazard evaluation was done on the data sets representing the two ways of shift scheduling. This was done through calculating the 'observed' PDA, i.e. for every event > mag. 1 actually recorded, the potential damage area was calculated similarly to the way it is done in the statistical analysis. Here the actual apparent stress is used rather than that inferred from the E-M relation, converted to stress drop through an empirical relation and then the same formulation is used to estimate the volume of rock shaken at a velocity greater than 1 m/s. The calculations were repeated for the same data sets, excluding the largest event in each set. The results, given in Table 4.5, show that, if the largest event is excluded in each case, the FULCO mining was indeed less hazardous.

.None of the above hazard parameters have been normalised to production. The significantly smaller production volume (2027 centares during the 11-day fortnight period vs. 1531 centares during FULCO) explains the lower Apparent Stress Level during the latter period. The increase in stiffness for the larger events has been speculated on in the previous section.

It is not clear how one should normalise for production. A simple division of the of the hazard parameter by the number of centares may be too simplistic. Although such an approach is probably reasonable for the hazard associated with small events, it is not valid for the hazard associated with the larger events. Since the larger events early in the 2nd period still relate to mining during the 1st period, they should be excluded in such an analysis, but such an approach creates new problems: there is no rule according to which a particular magnitude cut-off should be used to exclude those events which could occur by chance in any of the populations - see also section 3.2.1

As far as the fundamental problem addressed here is concerned, one can conclude that the changes in seismic hazard described above is most likely related to the changes in production rate and the 'active layout' caused by the concentration on high grade portion of the ore body, rather than the details of the shift schedules. In case A the paradox is that FULCO was, in fact, associated with lower production.

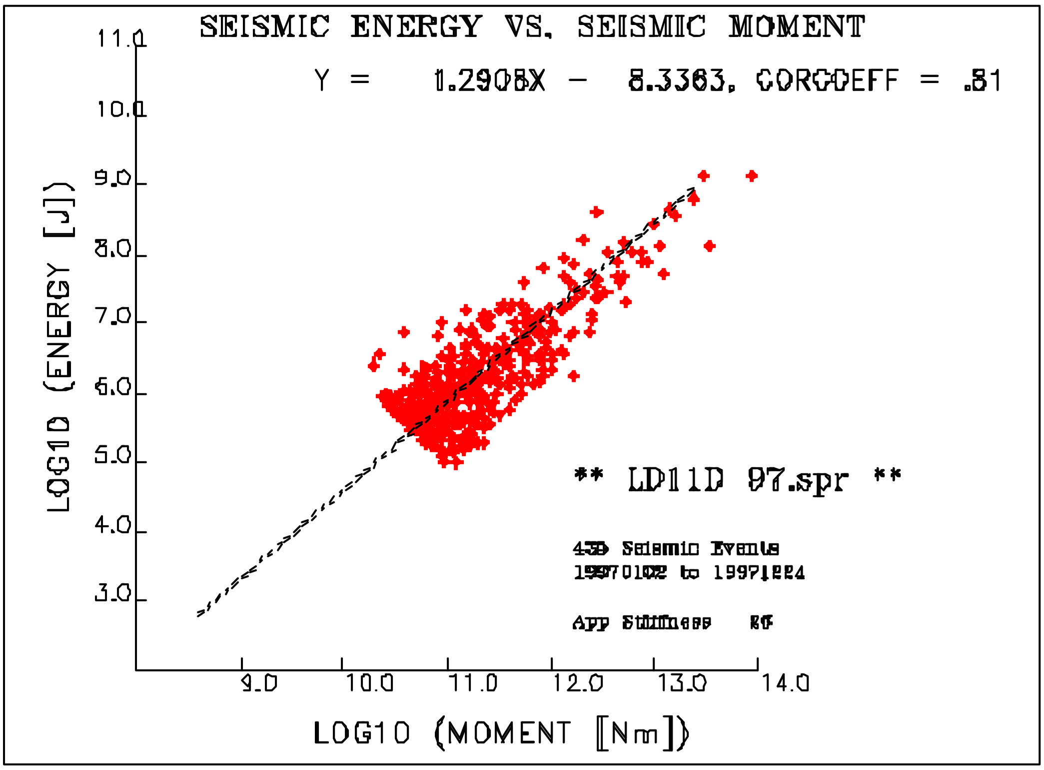

Figure 4.12. E-M relation for the larger events,11D FNT, Case A.

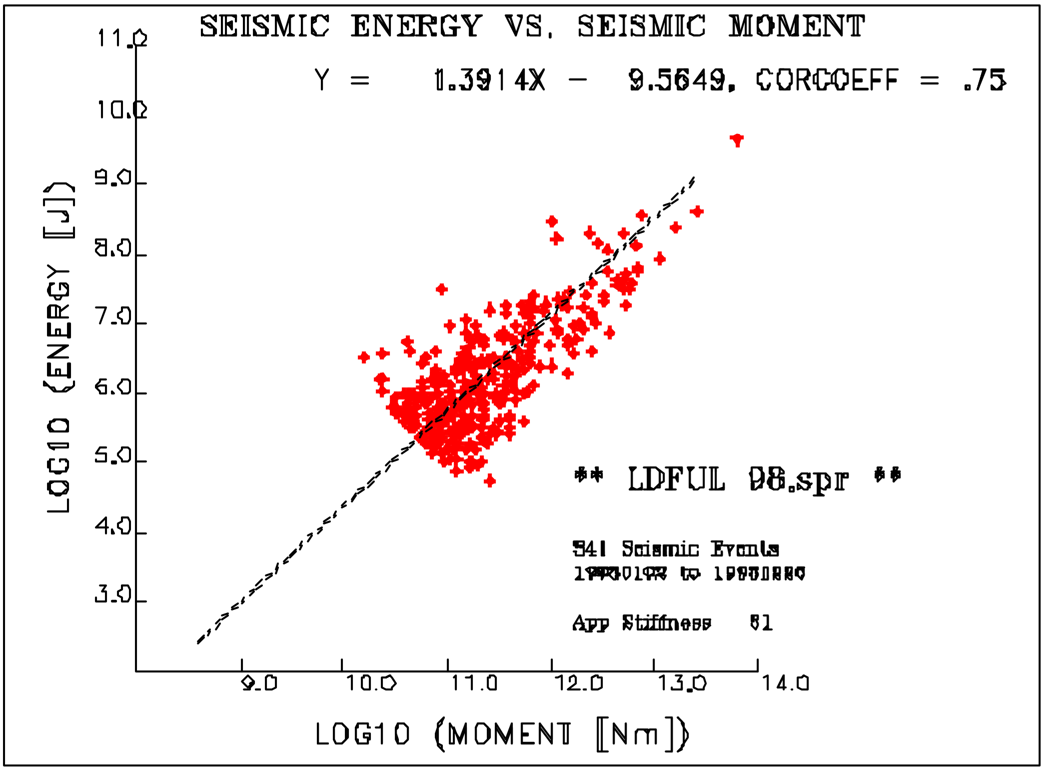

Figure 4.13. E-M relation for the larger events, FULCO, Case A.

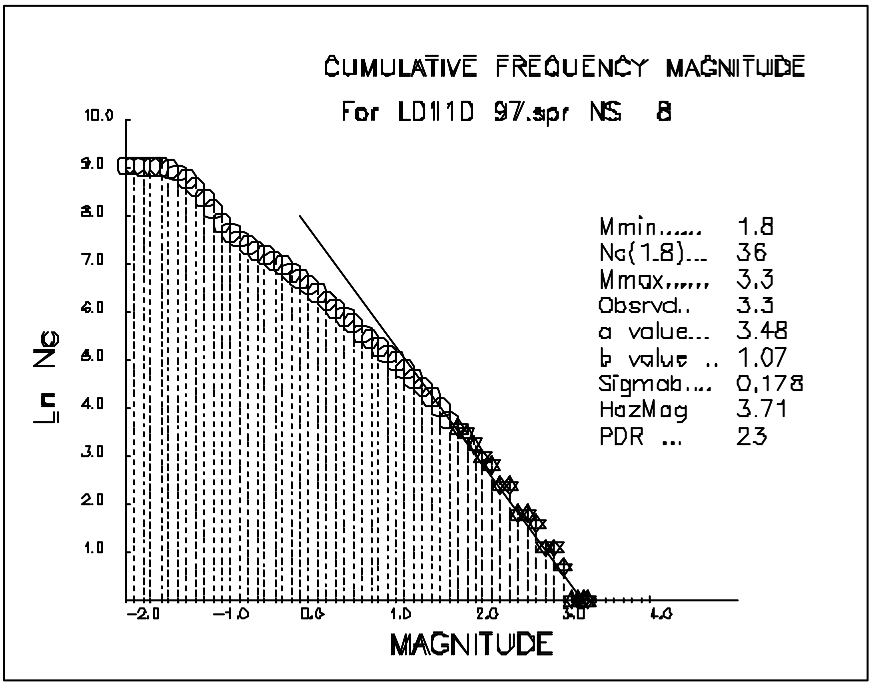

Figure 4.14. Gutenberg-Richter plot for 11-day fortnight operations, Case A. The line fitting is for events > local magnitude 1.8.

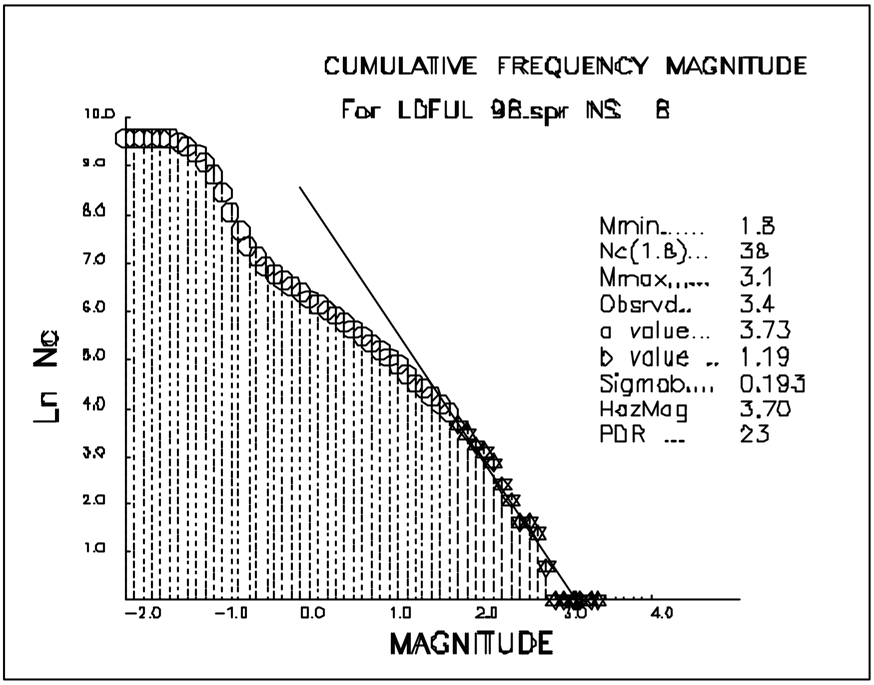

Figure 4.15. Gutenberg-Richter plot for FULCO, Case A. The line fitting is for events > local magnitude 1.8.

Table 4.6. Seismic hazard probability table 11D_fortnight operations, Case A

PROBABILITY OF OCCURRENCE OF A SEISMIC EVENT WITH MAGNITUDE NOT SMALLER THAN M GIVEN TIME t AND T(M) - MEAN RECURRENCE TIME FOR EVENTS WITH MAGNITUDES NOT SMALLER THAN M.

(time in months)

Observation period in months	=	12.0
Mmin	=	1.8
Mmax	=	3.3
Mmax observed	=	3.3
Delta M	=	.10
Beta	=	2.46
b-value	=	1.07
Total number of events	=	8559
N events with M>=Mmin	=	36
Hazard Magnitude	=	3.71
Hazard Magnitude per year	=	3.71
SumMo from freq-mag relation	=	.27E+15
SumE from freq-mag relation	=	.65E+10
Radius of potential damage	=	23
Area of potential damage	=	1694

RECCURRENCE TIMES AND EVENTS PER MONTH

M	.50	1.00	1.50	2.00	2.50	3.00
T(M)	.013	.046	.157	.555	2.143	13.186
T obs	.0316	.0723	.1739	.4614	1.9993	5.9980
N(M)	903.5	263.6	76.4	21.6	5.6	.9
N obs	380	166	69	26	6	2

t	PROBABILITY OF OCCURRENCE					
1.0	1.0000	1.0000	.9976	.8359	.3790	.0749
2	1.0000	1.0000	1.0000	.9707	.6120	.1441
3	1.0000	1.0000	1.0000	.9944	.7562	.2079
4	1.0000	1.0000	1.0000	.9988	.8459	.2669
5	1.0000	1.0000	1.0000	.9997	.9020	.3214
6	1.0000	1.0000	1.0000	.9999	.9374	.3717
7	1.0000	1.0000	1.0000	1.0000	.9598	.4182
8	1.0000	1.0000	1.0000	1.0000	.9740	.4612
9	1.0000	1.0000	1.0000	1.0000	.9831	.5009
10	1.0000	1.0000	1.0000	1.0000	.9890	.5376
11	1.0000	1.0000	1.0000	1.0000	.9928	.5716
12	1.0000	1.0000	1.0000	1.0000	.9952	.6030

Table 4.7. Seismic hazard probability table FULCO, Case A

PROBABILITY OF OCCURRENCE OF A SEISMIC EVENT WITH MAGNITUDE NOT SMALLER THAN M GIVEN TIME t AND T(M) - MEAN RECURRENCE TIME FOR EVENTS WITH MAGNITUDES NOT SMALLER THAN M.

(time in months)

Observation period in months	=	12.0
Mmin	=	1.8
Mmax	=	3.1
Mmax observed	=	3.4
Delta M	=	.10
Beta	=	2.75
b-value	=	1.19
Total number of events	=	14680
N events with M>=Mmin	=	38
Hazard Magnitude	=	3.70
Hazard Magnitude per year	=	3.70
SumMo from freq-mag relation	=	.27E+15
SumE from freq-mag relation	=	.60E+10
Radius of potential damage	=	23
Area of potential damage	=	1794

RECCURRENCE TIMES AND EVENTS PER MONTH

M	.50	1.00	1.50	2.00	2.50	3.00
T(M)	.009	.034	.136	.558	2.562	28.635
T obs	.0380	.0774	.1764	.4797	2.3986	11.9930
N(M)	1385.3	350.2	87.9	21.5	4.7	.4
N obs	316	155	68	25	5	1

t	PROBABILITY OF OCCURRENCE					
1.0	1.0000	1.0000	.9990	.8344	.3287	.0352
2	1.0000	1.0000	1.0000	.9703	.5475	.0691
3	1.0000	1.0000	1.0000	.9943	.6938	.1018
4	1.0000	1.0000	1.0000	.9988	.7920	.1333
5	1.0000	1.0000	1.0000	.9997	.8582	.1637
6	1.0000	1.0000	1.0000	.9999	.9029	.1930
7	1.0000	1.0000	1.0000	1.0000	.9333	.2213
8	1.0000	1.0000	1.0000	1.0000	.9540	.2485
9	1.0000	1.0000	1.0000	1.0000	.9682	.2748
10	1.0000	1.0000	1.0000	1.0000	.9779	.3001
11	1.0000	1.0000	1.0000	1.0000	.9846	.3245
12	1.0000	1.0000	1.0000	1.0000	.9893	.3480

4.2. Case Study B

The following analyses were performed using data from a shaft pillar complex being mined in the West Wits area. Data was taken from two 10-month time periods, one in 11-day fortnight and one in FULCO. The fact that pillar mining is dominant in the study area is significant since, with progressive mining, pillar size decrease and seismic hazard generally increases. Any conclusions about the effect of changing scheduling procedures during pillar extraction must be made with this in mind.

4.2.1. Seismic Exposure Analysis

Table 4.8 contains 11-day fortnight data referring to time of day distribution of personnel in stopes and mine wide as well as seismic events with magnitude >1.0 and 2.0. This data is presented, in part, in graphical form in Figures 4.16 and 4.17. 'Potential problem times' for the events >1.0 include the 12^{th} and 13^{th} hours. Other significant contributions to Daily SE come from the 5^{th} to 9^{th} hours, although (with exception to the 5^{th} hour) these are significant due to number of personnel and not due to high seismic activity. Not accounting for the moderate SE produced by the 7^{th} hour, there are no times when SE is significantly high for the >2.0 data. However, this database is limited and results of SE analysis on any less than a year of data should be treated with caution, particularly when analyzing areas of low to moderate seismic activity.

Table 4.9 and Figures 4.18 and 4.19 contain the same data as above but for FULCO. The most remarkable observation to be made for the events with magnitude >1.0 is the relatively large contribution to SE made by the 6^{th} hour (a third of the daily SE). Other 'potential problem times' include the 7^{th} to 10^{th} hours. Other times with relatively high seismic activity are the 1^{st}, 22^{nd} and 24^{th} hours. For events with magnitudes >2.0, 'potential problem times' are the 6^{th}, 9^{th} and 10^{th} hours with, remarkably, no activity occurring during any other times.

Daily SE per Centare for 11-day fortnight and FULCO are presented in Table 4.10. SE is notably higher in the case of FULCO. Perhaps the largest contributing factor to this increase is the greater number of personnel on the day shift of FULCO mining. Unskilled labor increased by 2/3 making significant contributions to SE when seismic activity was high (such as in the 6^{th} hour). Another significant factor, the increased seismicity, may be explained by the increased production and by the fact that the area is becoming increasingly stressed as the pillar is mined out.

4.2.2. Gutenberg-Richter and Energy-Moment Analysis

Figures 4.20 and 4.21 and Tables 4.11 to 4.13 represent statistical seismic hazard analyses. Figure 4.20 shows Gutenberg-Richter plots for 11-day fortnight and FULCO data using the local mine-magnitude relation. The Aki method is used with m_{min} set at 1.4. There are three populations in both cases:

1. Events < mag. –1.0, defining a steep *b*-slope,
2. Events > mag. –1.0 and < mag. 1.3, defining a shallower *b*-slope, and
3. Events > mag. 1.4, defining a steeper *b*-slope.

The size distribution for population 3 of the 11-day fortnight data appears incomplete in the sense that the G-R plot tail end is curving downwards sharply and a big gap exists between the largest and second largest events. Line fitting in this part of the G-R plot is not really possible and the *b*-value was fixed at 1.05, i.e. the same as for the FULCO data set. The *d*-values for the larger events are well defined (Figure 4.20) and it drops from 1.55 for the 11-day fortnight case to 1.48 for FULCO. The full statistical hazard calculations given in Tables 4.11 to 4.13 show no significant difference in seismic hazard between 11-day fortnight and FULCO operations, despite a greater activity rate during the latter phase.

Figure 4.21 also shows Gutenberg-Richter plots of 11-day fortnight and FULCO data for the third population, both using the Hanks Kanamori Moment relation for magnitude and the Gibowicz Energy relation for magnitude. Unlike for the local magnitude case (Figure 4.20) the *b*-values were successfully calculated using Aki's method. In both cases (moment- and energy magnitude) we observe a steeper *b*-slope for the FULCO data indicating a stiffer system under this scheduling procedure. The similar PDR values reflected in these figures between 11-day fortnight and FULCO confirms the fact that no significant difference in the general seismic hazard occurred. .

Despite a lower *d*-value for the FULCO period, the Apparent Stiffness is marginally greater (Table 4.11). This is because of the increased intercept of the E-M relation as reflected by a significantly higher apparent stress level. This is explained by the fact that production increased significantly (40105 to 50503 centares) and that the remainder of the pillar area being mined reduced, increasing the load.

The slight general increase in system stiffness, as indicated by the slight increases in *b*-values and Apparent Stiffness could possibly be attributed to a greater stiffness response due to the higher mining rate, the rockmass not being able to relax fast enough. This concept may allow a high rate of mining towards solid rock. Such a situation is, however, not sustainable in the case of pillar mining, because, sooner or later this temporary 'work hardening' with increased stress will be replaced by softening. In the particular case of the area of interest here, the seismic hazard eventually did increase and mining was terminated in a large region of the complex after the time period of this study.

4.2.3. Conclusions

The overall seismic hazard for Case B did not increase despite an increase in production because of a slight increase system stiffness in response to a higher rate of loading. The increased deployment of production staff and the unfavourable time of day distribution, however, caused a significant increase in SE. The work hardening due to the high loading rate could not be sustained in the pillar-mining environment and the seismic hazard increased in part of the area of study to such an extent that mining had to be terminated in part.

Table 4.8. SE calculations for case B - 11-day fortnight operations

Hour of Day	N > 1.0	Avg. N > 1.0	Men exposed in prod. day	Hourly SE	Events >0.0 Prorated to 1.0	Avg. N Prorated	Hourly SE Prorated
1st	3	0.0128	108	1.38	10.98	0.0469	5.07
2nd	0	0.0000	108	0.00	8.65	0.0370	3.99
3rd	5	0.0214	108	2.31	3.53	0.0151	1.63
4th	5	0.0214	108	2.31	2.45	0.0105	1.13
5th	7	0.0299	108	3.23	6.49	0.0277	3.00
6th	3	0.0128	300	3.85	96.17	0.4110	123.29
7th	3	0.0128	315	4.04	6.87	0.0294	9.25
8th	3	0.0128	315	4.04	11.59	0.0495	15.60
9th	2	0.0085	315	2.69	68.69	0.2935	92.47
10th	1	0.0043	315	1.35	38.59	0.1649	51.95
11th	1	0.0043	315	1.35	7	0.0299	9.42
12th	7	0.0299	315	9.42	8.12	0.0347	10.93
13th	6	0.0256	315	8.08	0.69	0.0029	0.93
14th	4	0.0171	0	0.00	41.92	0.1791	0.00
15th	16	0.0684	0	0.00	124.47	0.5319	0.00
16th	18	0.0769	0	0.00	69.45	0.2968	0.00
17th	14	0.0598	0	0.00	155.22	0.6633	0.00
18th	11	0.0470	0	0.00	141.03	0.6027	0.00
19th	17	0.0726	0	0.00	25.56	0.1092	0.00
20th	4	0.0171	0	0.00	38.07	0.1627	0.00
21st	2	0.0085	0	0.00	95.23	0.4070	0.00
22nd	4	0.0171	100	1.71	12.57	0.0537	5.37
23rd	4	0.0171	108	1.85	10.57	0.0452	4.88
24th	2	0.0085	108	0.92	21.85	0.0934	10.08
Daily totals				48.52			348.99
		Number of Production Days: 234 Total Number of Days: 315					

Table 4.9. SE calculations for case B - FULCO

Hour of Day	N > 1.0	Avg. N > 1.0	Men exposed in prod. day	Hourly SE	Events >0.0 Prorated to 1.0	Avg. N Prorated	Hourly SE Prorated
1st	6	0.0256	108	2.77	25.06	0.1071	11.57
2nd	2	0.0085	108	0.92	1	0.0043	0.46
3rd	2	0.0085	108	0.92	235.51	1.0065	108.70
4th	0	0.0000	108	0.00	46.09	0.1970	21.27
5th	1	0.0043	108	0.46	41.42	0.1770	19.12
6th	14	0.0598	500	29.91	28.83	0.1232	61.60
7th	4	0.0171	515	8.80	67.39	0.2880	148.32
8th	3	0.0128	515	6.60	11.86	0.0507	26.10
9th	4	0.0171	515	8.80	17.85	0.0763	39.29
10th	3	0.0128	515	6.60	3.51	0.0150	7.73
11th	1	0.0043	515	2.20	2.7	0.0115	5.94
12th	2	0.0085	515	4.40	10.96	0.0468	24.12
13th	0	0.0000	515	0.00	14.08	0.0602	30.99
14th	12	0.0513	0	0.00	12.21	0.0522	0.00
15th	17	0.0726	0	0.00	90.1	0.3850	0.00
16th	25	0.1068	0	0.00	66.77	0.2853	0.00
17th	40	0.1709	0	0.00	62.27	0.2661	0.00
18th	18	0.0769	0	0.00	36.17	0.1546	0.00
19th	5	0.0214	0	0.00	81.19	0.3470	0.00
20th	5	0.0214	0	0.00	42.03	0.1796	0.00
21st	6	0.0256	0	0.00	14.87	0.0635	0.00
22nd	7	0.0299	100	2.99	12.88	0.0550	5.50
23rd	5	0.0214	108	2.31	19.6	0.0838	9.05
24th	8	0.0342	108	3.69	9.77	0.0418	4.51
Daily Totals:				81.40			524.26
			Number of Production Days:	301			
			Total Number of Days:	315			

Table 4.10. Summary of SE calculations for case B

	11-day Fortnight	FULCO
SE/day	48.52	81.40
N prod. Days	234	301
Centares produced	40105	50503
SE/centare	0.2831	0.4851

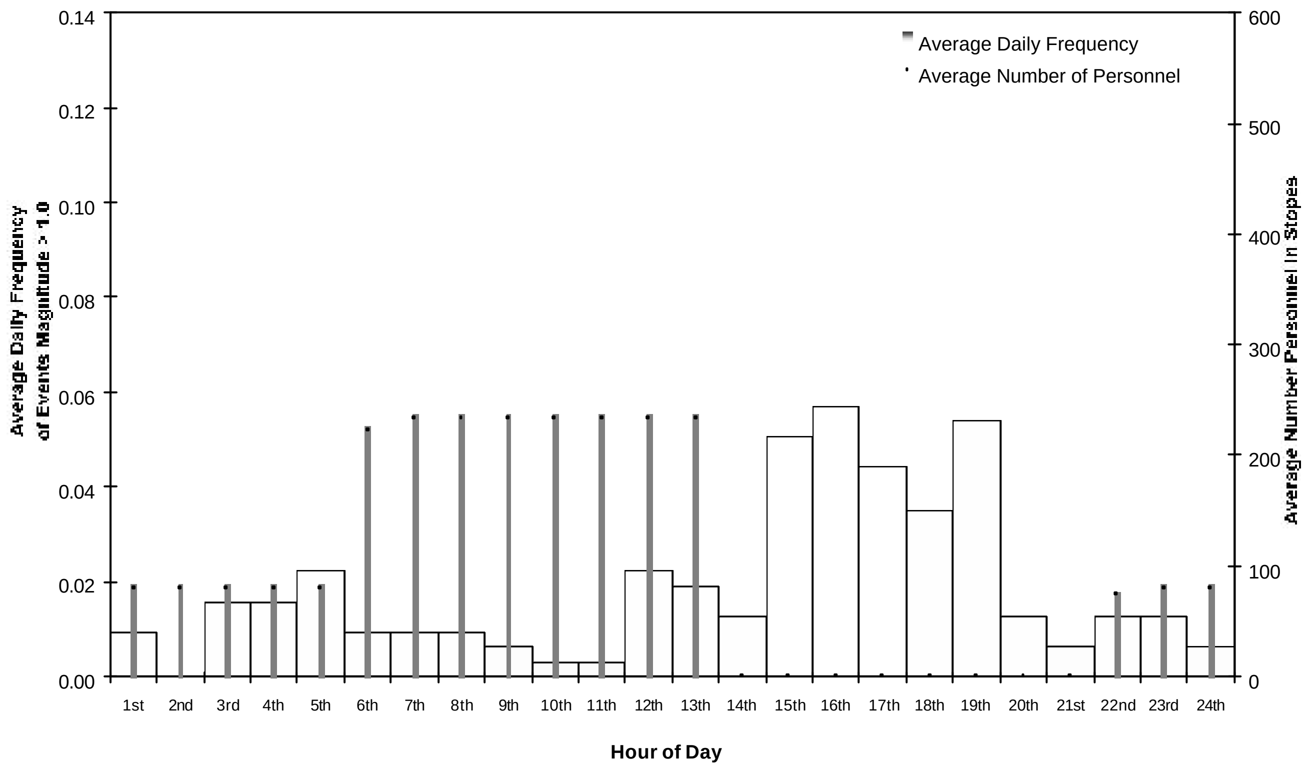

Figure 4.16. Personnel in Stopes and Event Frequency > 1.0 Time of Day Distributions for 11-day Fortnight - Case B.

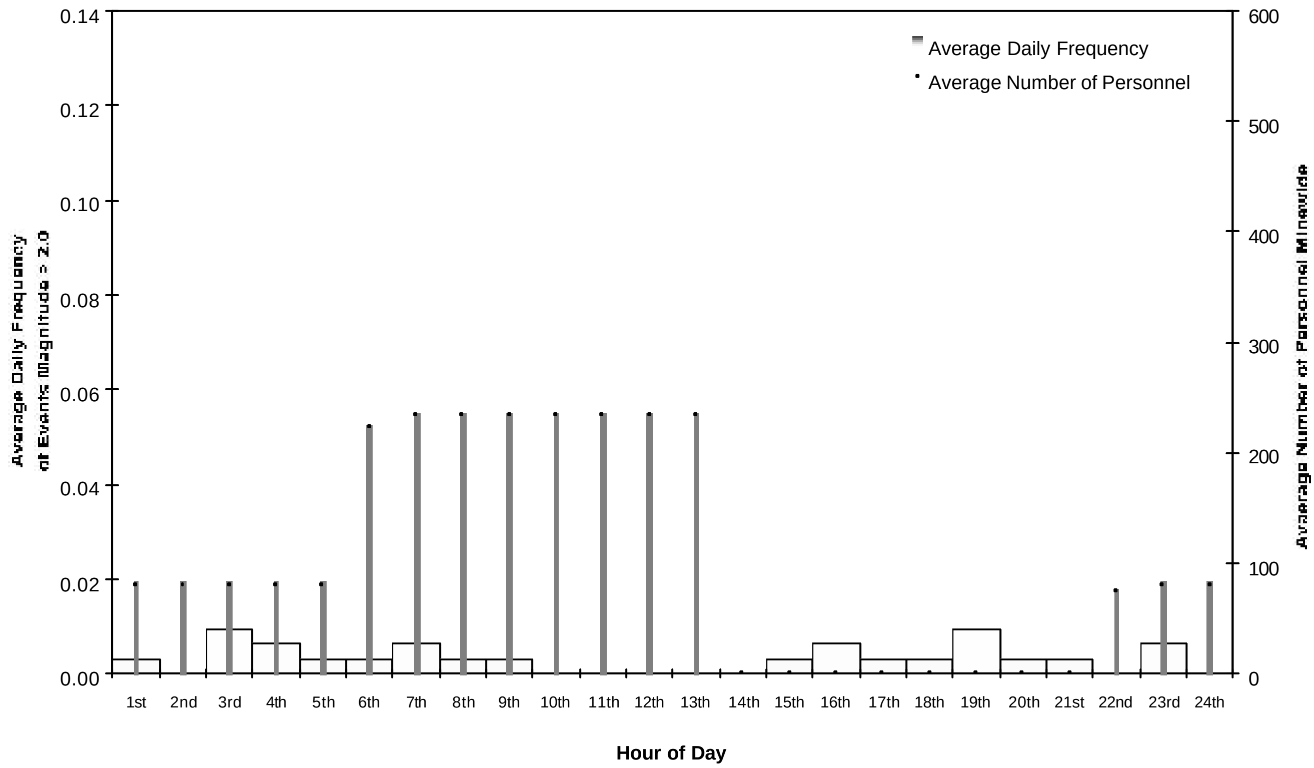

Figure 4.17. Personnel Underground and Event Frequency > 2.0 Time of Day Distributions for 11-day Fortnight - Case B.

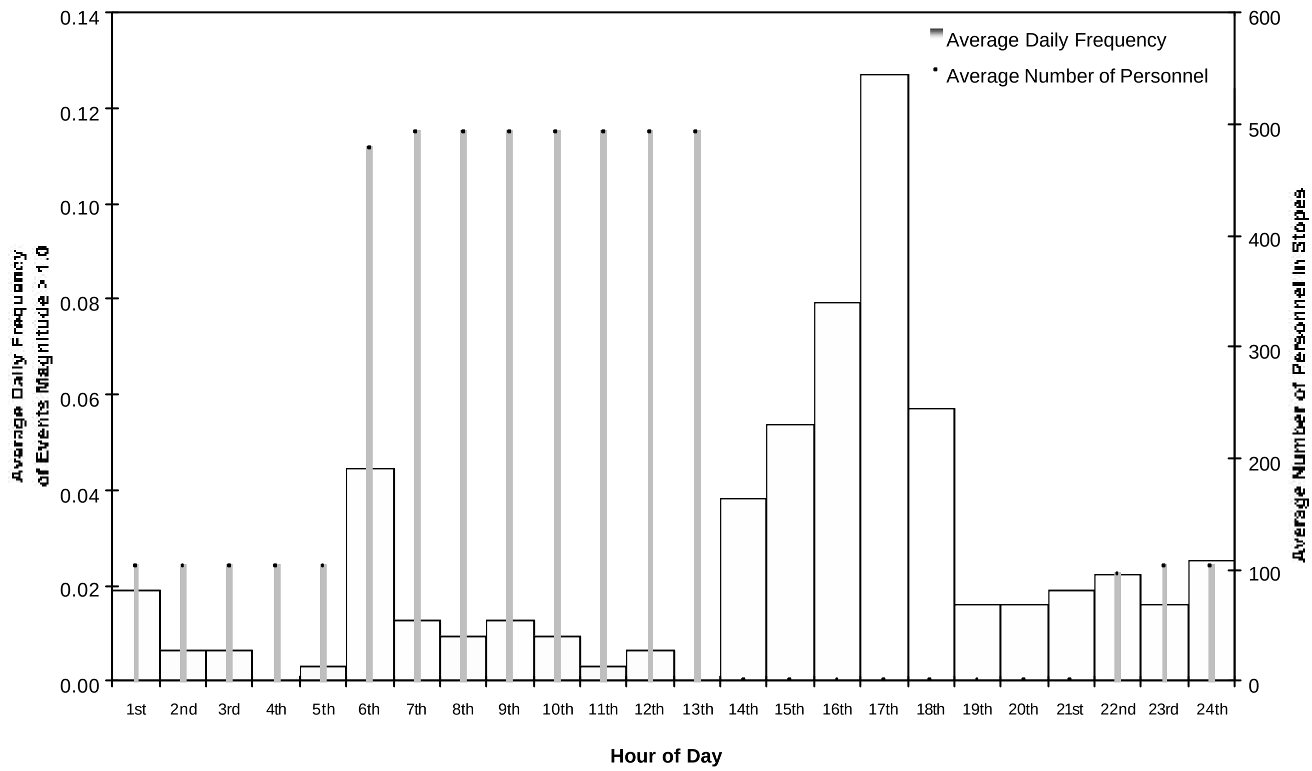

Figure 4.18. Personnel in stopes and Event Frequency >1.0 time of day distributions for FULCO - Case B.

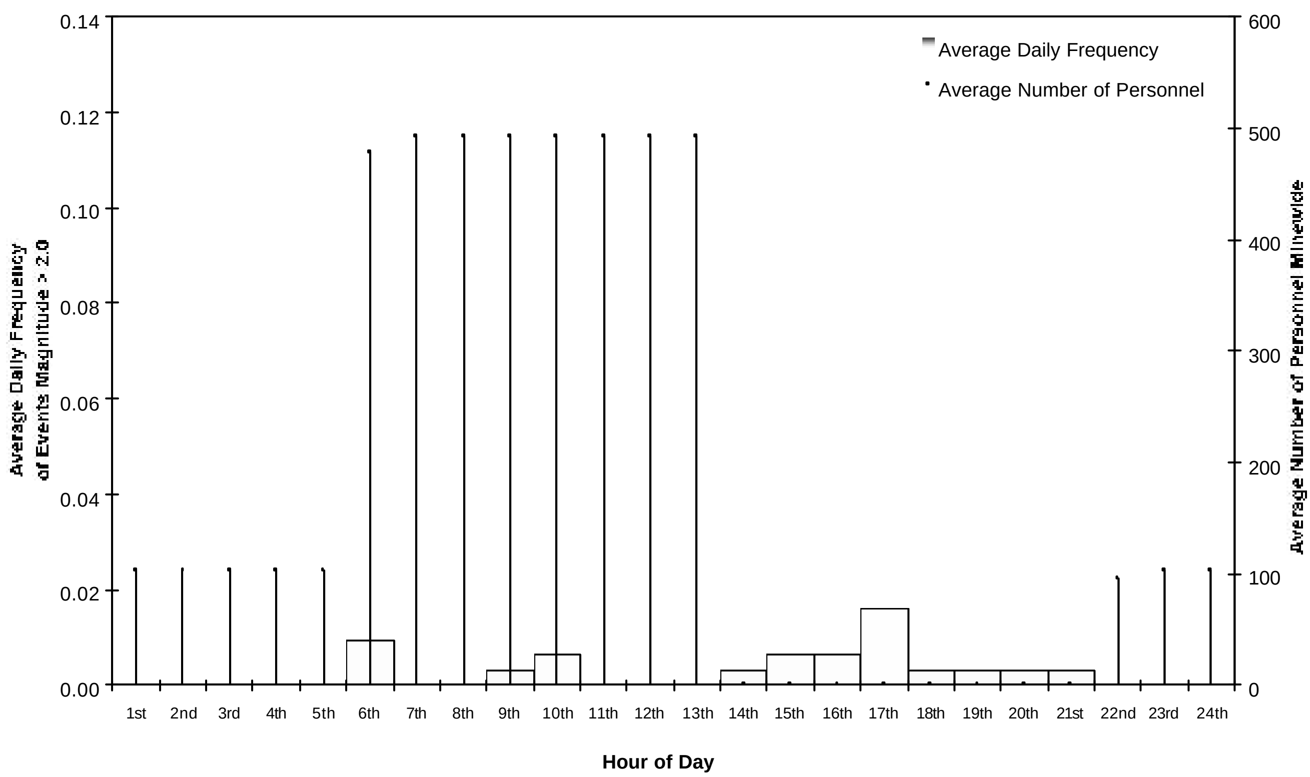

Figure 4.19. Personnel Underground and Event Frequency >2.0 time of day distributions for FULCO - Case B

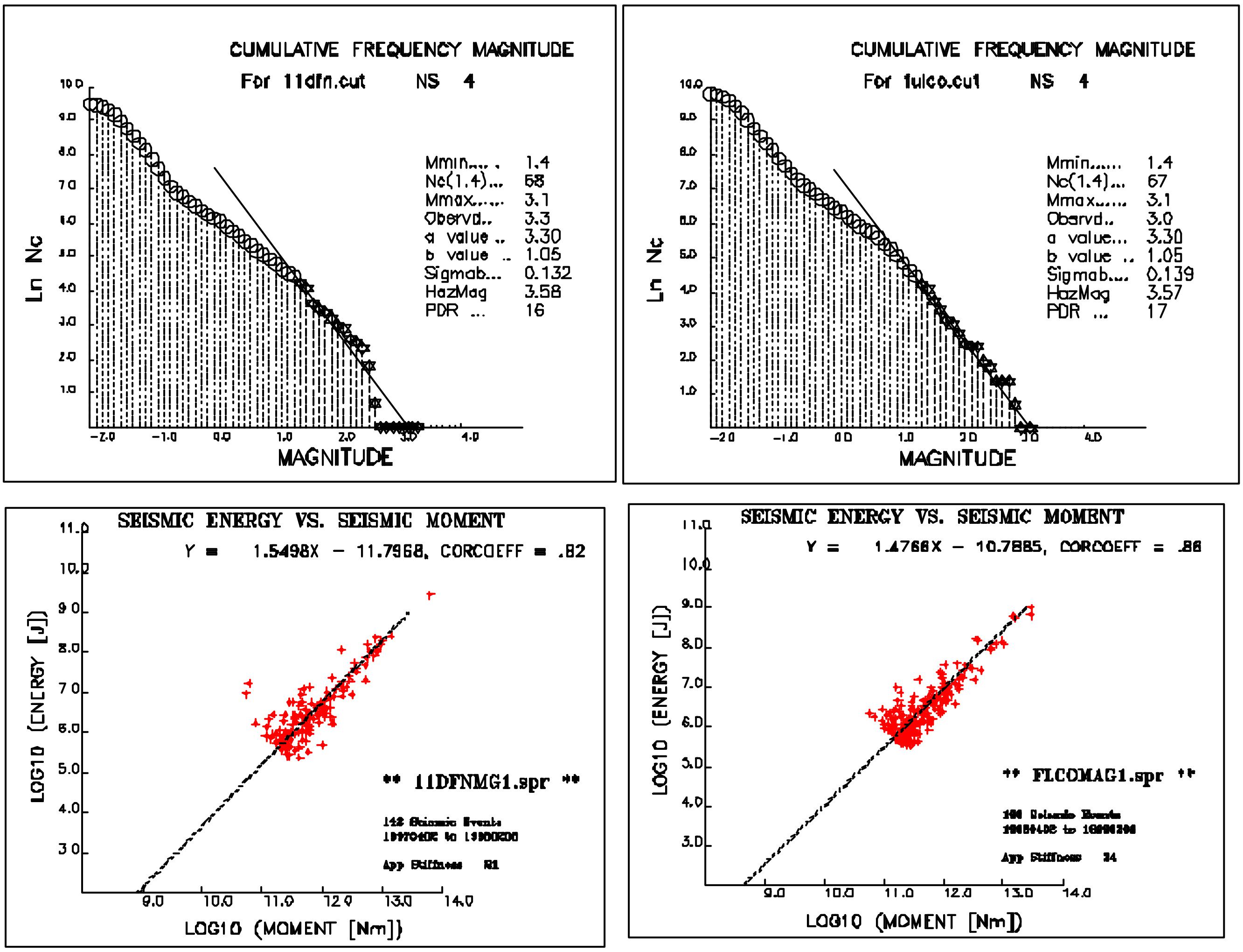

Figure 4.20. Case-B: Gutenberg-Richter- and E-M plots for 11-day fortnight (left) and FULCO (right). The G-R plots are based on local magnitude.

Table 4.11. Summary of Gutenberg-Richter and E-M statistics for Case B

	d-slope	c_value	Ap.Stff[MPa]	App.Str.L[KPa]
11DFRT_B	1.54980	-11.79682	21.28	185.52
FULCO_ B	1.47658	-10.78853	24.23	258.90

	b-val	Mmin	Mmax	Hazmag	PDA	PDR
11DFRT_B	1.05	1.40	3.15	3.64	828	16
FULCO_ B	1.05	1.40	3.14	3.63	930	17

Table 4.12. Probability table for Case B, 11-day fortnight (local magnitude)

PROBABILITY OF OCCURRENCE OF A SEISMIC EVENT WITH MAGNITUDE NOT SMALLER THAN M GIVEN TIME t AND T(M) - MEAN RECURRENCE TIME FOR EVENTS WITH MAGNITUDES NOT SMALLER THAN M.

(time in months)

Observation period in months	=	10.3
Mmin	=	1.4
Mmax	=	3.1
Mmax observed	=	3.3
Delta M	=	.10
Beta	=	2.42
b-value	=	1.05
Total number of events	=	12956
N events with M>=Mmin	=	68
Hazard Magnitude	=	3.58
Hazard Magnitude per year	=	3.64
SumMo from freq-mag relation	=	.25E+15
SumE from freq-mag relation	=	.43E+10
Radius of potential damage	=	16
Area of potential damage	=	828

RECCURRENCE TIMES AND EVENTS PER MONTH

M	.50	1.00	1.50	2.00	2.50	3.00
T(M)	.017	.057	.194	.680	2.702	24.145
T obs	.0441	.0866	.1778	.5155	1.7183	10.3100
N(M)	607.0	180.5	53.2	15.2	3.8	.4
N obs	234	119	58	20	6	1

t	PROBABILITY OF OCCURRENCE					
1.0	1.0000	1.0000	.9936	.7716	.3123	.0411
2	1.0000	1.0000	.9999	.9462	.5262	.0806
3	1.0000	1.0000	1.0000	.9869	.6728	.1184
4	1.0000	1.0000	1.0000	.9967	.7737	.1546
5	1.0000	1.0000	1.0000	.9992	.8431	.1893
6	1.0000	1.0000	1.0000	.9998	.8910	.2225
7	1.0000	1.0000	1.0000	.9999	.9242	.2544
8	1.0000	1.0000	1.0000	1.0000	.9471	.2849
9	1.0000	1.0000	1.0000	1.0000	.9631	.3142
10	1.0000	1.0000	1.0000	1.0000	.9742	.3423
11	1.0000	1.0000	1.0000	1.0000	.9819	.3692
12	1.0000	1.0000	1.0000	1.0000	.9873	.3950

Table 4.13. Probability table for Case B, FULCO (local magnitude)

PROBABILITY OF OCCURRENCE OF A SEISMIC EVENT WITH MAGNITUDE NOT SMALLER THAN M GIVEN TIME t AND T(M) - MEAN RECURRENCE TIME FOR EVENTS WITH MAGNITUDES NOT SMALLER THAN M.

(time in months)

Observation period in months	=	10.3
Mmin	=	1.4
Mmax	=	3.1
Mmax observed	=	3.0
Delta M	=	.10
Beta	=	2.42
b-value	=	1.05
Total number of events	=	17686
N events with M>=Mmin	=	67
Hazard Magnitude	=	3.57
Hazard Magnitude per year	=	3.63
SumMo from freq-mag relation	=	.23E+15
SumE from freq-mag relation	=	.45E+10
Radius of potential damage	=	17
Area of potential damage	=	930

RECCURRENCE TIMES AND EVENTS PER MONTH

M	.50	1.00	1.50	2.00	2.50	3.00
T(M)	.017	.058	.197	.691	2.756	25.428
T obs	.0313	.0670	.1811	.6451	1.7202	10.3210
N(M)	598.2	177.9	52.4	14.9	3.7	.4
N obs	330	154	57	16	6	1

t	PROBABILITY OF OCCURRENCE					
1.0	1.0000	1.0000	.9930	.7660	.3074	.0391
2	1.0000	1.0000	.9999	.9436	.5193	.0767
3	1.0000	1.0000	1.0000	.9860	.6658	.1128
4	1.0000	1.0000	1.0000	.9964	.7671	.1474
5	1.0000	1.0000	1.0000	.9991	.8375	.1807
6	1.0000	1.0000	1.0000	.9997	.8863	.2126
7	1.0000	1.0000	1.0000	.9999	.9203	.2433
8	1.0000	1.0000	1.0000	1.0000	.9441	.2728
9	1.0000	1.0000	1.0000	1.0000	.9607	.3011
10	1.0000	1.0000	1.0000	1.0000	.9723	.3283
11	1.0000	1.0000	1.0000	1.0000	.9804	.3544
12	1.0000	1.0000	1.0000	1.0000	.9862	.3795

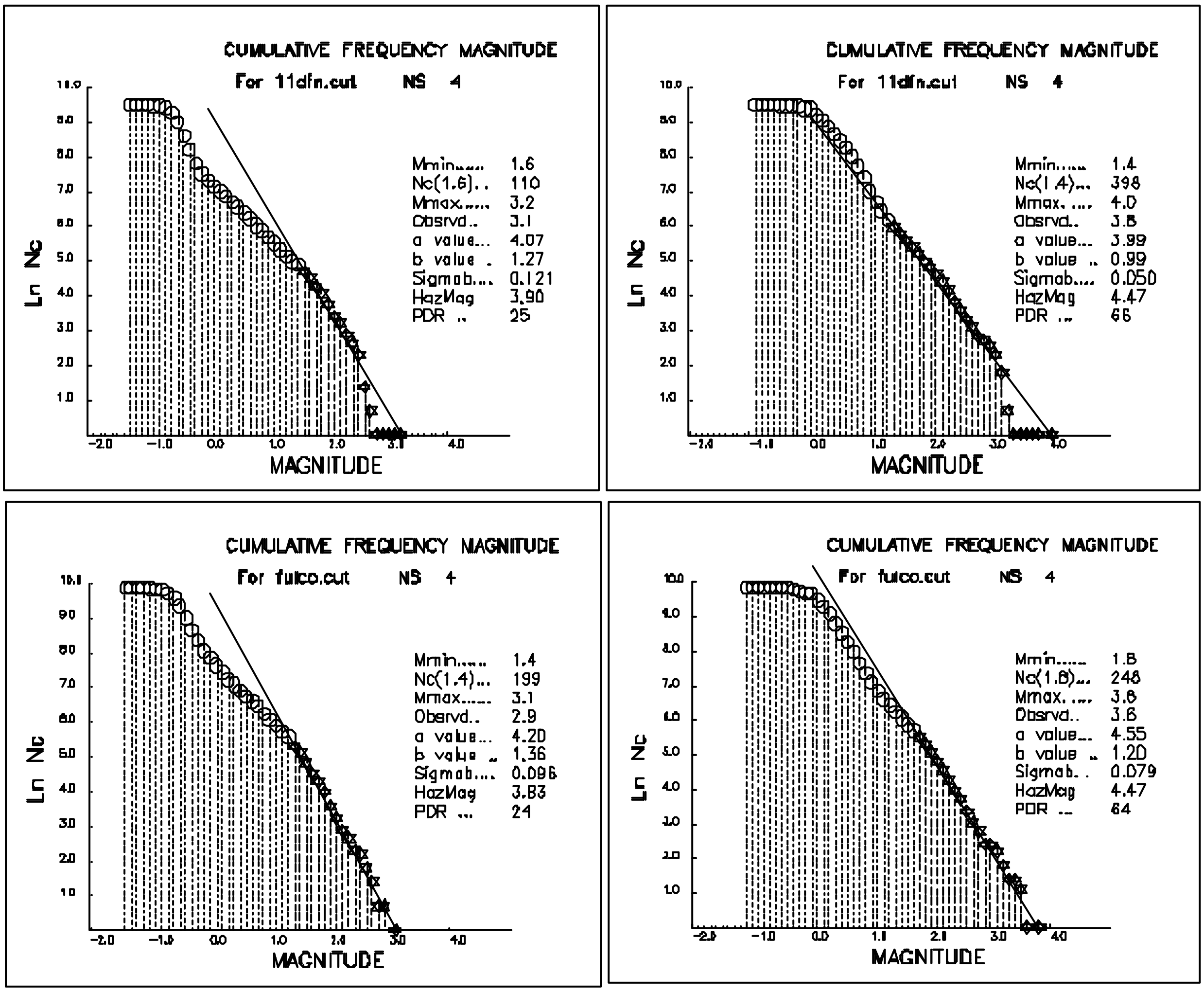

Figure 4.21. More Gutenberg-Richter plots for Case B. Top left is for 11 day fortnight, Hanks-Kanamori moment magnitude. Bottom left is the same for FULCO. Top right the plot for 11 day fortnight using the Gibowicz energy-magnitude, while bottom right is the same for FULCO.

4.3. Case study C

Case C is from a mine in the Klerksdorp gold field. In the particular area of the mine selected for the study the layout is scattered and the area mined included the partial extraction of a large shaft pillar.

Production and manpower data was made available for a 15 month period of 11 day fortnight mining and an 8 month period of FULCO. For a 12 month period separating these two time spans, only seismic data and no production or manpower data could be found.

4.3.1. Seismic exposure analysis

Table 4.14a and b show time of day distributions of personnel and seismic events with magnitudes > 1 (also number of events > mag 0 , prorated to mag 1) for the 11 day fortnight and the one FULCO period. The data is graphically illustrated in Figure 4.22a and b and summarised in Table 4.15

The time of day distribution of seismic events was unfavourable in the case of 11 day fortnight operations (Figure 4.22a). This worsened during the FULCO period (Figure 4.22b). Hours of the day that are potentially characterised by high SE can be identified from inspecting columns 5 and 8 of Table 4.14. In the 11-day fortnight case the worst time is from 10h00 -15h00. In FULCO case, peaks in SE occur during the 5th, 10th, 13th ,19th and 24th hours of the day. The result of this high 'off shift' seismic activity is a high (the highest by far of those data sets analysed) daily SE rating of 208. The SE/centare mined is also the highest found. The reasons for the anomalous activity, especially near midnight, appears to be uncontrolled blasting - this is clearly an unacceptable situation. FULCO mining has since stopped at the site of Case C and improved control over blasting has removed the anomalous seismic activity around midnight.

Table 4.14a. Time of day personnel distribution, frequency rates and seismic exposure for 11-day fortnight operations - Case C.

Hour of Day	N > 1.0	Avg. N >1	Workers exposed in prod. day	Hourly SE	Events >0.0 Prorated to 1.0	Avg. N Prorated	Hourly SE Prorated
1st	5	0.0137	272	3.73	15.96	0.0437	11.89
2nd	6	0.0164	272	4.47	17.73	0.0486	13.21
3rd	5	0.0137	262	3.59	12.87	0.0353	9.24
4th	5	0.0137	262	3.59	26.51	0.0726	19.03
5th	6	0.0164	262	4.31	16.98	0.0465	12.19
6th	5	0.0137	10	0.14	21.28	0.0583	0.58
7th	3	0.0082	761	6.25	8.32	0.0228	17.35
8th	3	0.0082	761	6.25	13.26	0.0363	27.65
9th	1	0.0027	761	2.08	5.43	0.0149	11.32
10th	5	0.0137	761	10.42	86.46	0.2369	180.26
11th	6	0.0164	761	12.51	28.09	0.0770	58.57
12th	5	0.0137	761	10.42	14.24	0.0390	29.69
13th	2	0.0055	761	4.17	67.38	0.1846	140.48
14th	8	0.0219	761	16.68	48.28	0.1323	100.66
15th	1	0.0027	743	2.04	8.23	0.0225	16.75
16th	11	0.0301	0	0.00	57.56	0.1577	0.00
17th	7	0.0192	0	0.00	23.78	0.0652	0.00
18th	10	0.0274	0	0.00	124.76	0.3418	0.00
19th	5	0.0137	272	3.73	18.21	0.0499	13.57
20th	9	0.0247	272	6.71	30.44	0.0834	22.68
21st	6	0.0164	272	4.47	21.98	0.0602	16.38
22nd	6	0.0164	272	4.47	33.03	0.0905	24.61
23rd	6	0.0164	272	4.47	27.64	0.0757	20.60
24th	2	0.0055	272	1.49	29.49	0.0808	21.98
Daily Totals:				115.99			768.69
				Number of Production Days:		365	
				Total Number of Days:		486	

Table 4.14b. Time of day personnel distribution, frequency rates and seismic exposure for FULCO operations - Case C.

Hour of Day	N 1.0	Avg.N>1	Workers exposed in prod. day	Hourly SE	Events >0.0 Prorated to 1.0	Avg. N Prorated	Hourly SE
1st	9	0.0407	272	11.08	24.49	0.1109	30.16
2nd	5	0.0226	272	6.16	38.09	0.1725	46.91
3rd	1	0.0045	262	1.19	11.52	0.0522	13.66
4th	6	0.0272	262	7.12	45.44	0.2057	53.90
5th	9	0.0407	262	10.68	117.15	0.5304	138.96
6th	6	0.0272	10	0.27	66.98	0.3032	3.03
7th	2	0.0091	761	6.89	12.09	0.0547	41.65
8th	7	0.0317	761	24.12	18.88	0.0855	65.05
9th	3	0.0136	761	10.34	21.55	0.0976	74.25
10th	6	0.0272	761	20.67	44	0.1992	151.60
11th	1	0.0045	761	3.45	8.54	0.0387	29.42
12th	5	0.0226	761	17.23	19.47	0.0881	67.08
13th	7	0.0317	761	24.12	26.06	0.1180	89.79
14th	4	0.0181	761	13.78	18.65	0.0844	64.26
15th	5	0.0226	743	16.82	20.55	0.0930	69.13
16th	6	0.0272	0	0.00	30.83	0.1396	0.00
17th	7	0.0317	0	0.00	33.97	0.1538	0.00
18th	6	0.0272	0	0.00	37.07	0.1678	0.00
19th	6	0.0272	272	7.39	69.11	0.3129	85.11
20th	6	0.0272	272	7.39	23.2	0.1050	28.57
21st	3	0.0136	272	3.69	32.03	0.1450	39.44
22nd	7	0.0317	272	8.62	26.22	0.1187	32.29
23rd	8	0.0362	272	9.85	52.99	0.2399	65.26
24th	14	0.0634	272	17.24	82.31	0.3727	101.36
Daily Totals:				228.08			1290.88
			Number of Production Days:		221		
			Total Number of Days:		231		

Table 4.15. Summary of SE calculations for Case C.

	11-day Fortnight	**FULLCO**
SE/day	115.99	228.08
N prod. Days	365	221
Centares produced	75110	85583
SE/centare	0.5637	0.5890

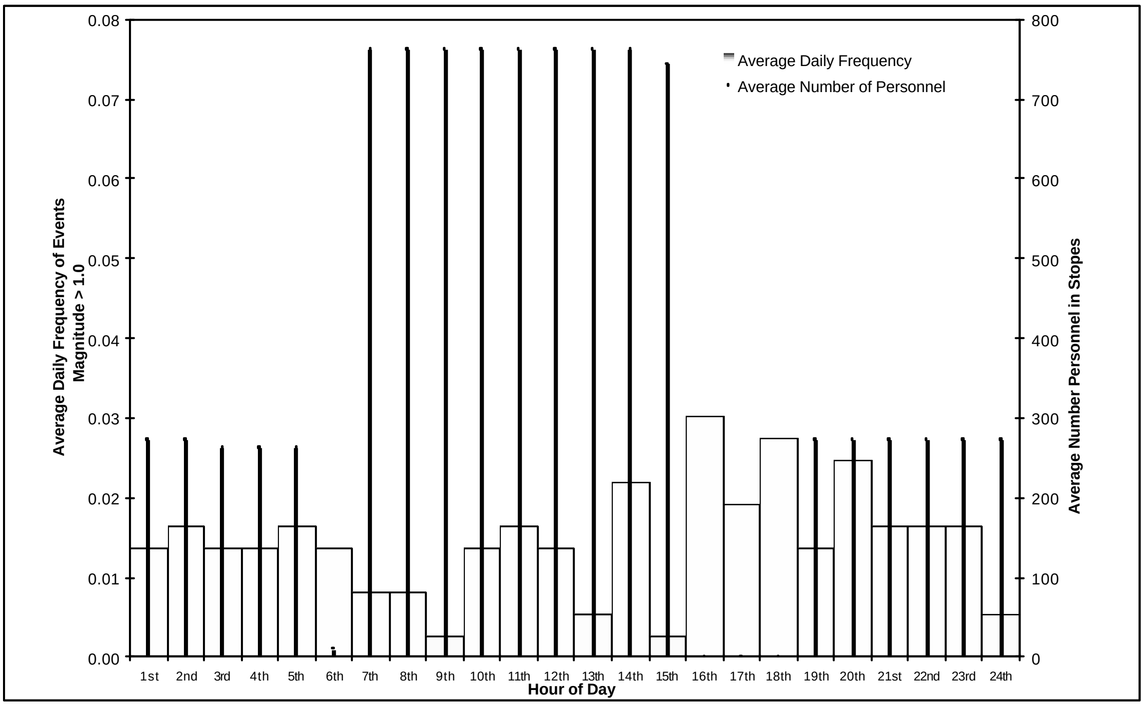

Figure 4.22a. Graphical representation of time of day seismic distribution of seismic events and underground workers - Case C - 11-day fortnight

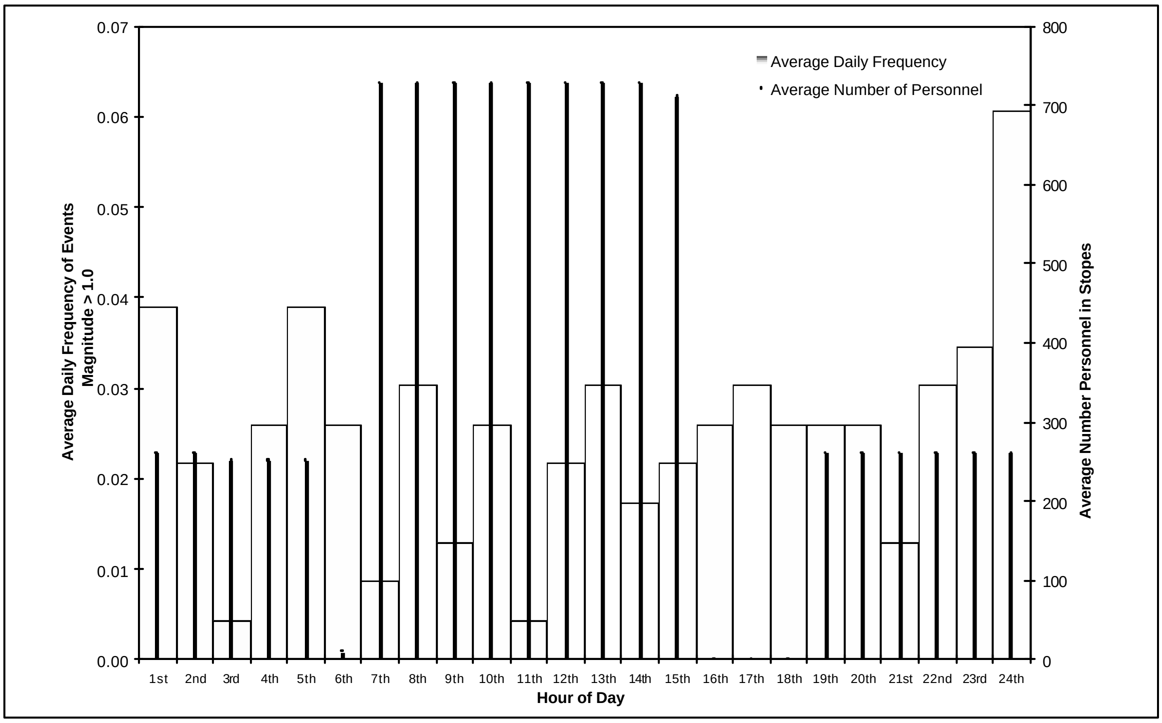

Figure 4.22b. Graphical representation of time of day seismic distribution of seismic events and underground workers - Case C - FULCO

4.3.2. Gutenberg–Richter and Energy-Moment analysis

The E-M and G-R statistics are based on the analyses shown graphically in Figs. 4.23 and 4.24 and is summarised in Table 4.18. Gutenberg-Richter statistics are detailed in Tables 4.16 and 4.17 a and b.

The *d*-value, Apparent Stiffness and Apparent Stress Level values remain almost unchanged from the 11-day fortnight period to the first 12 months of FULCO. Probably a higher production rate was only achieved during the second FULCO period, because here the *d*-value, Apparent Stiffness and Apparent Stress Level all increased. These increases are significant since they are still reflected in analyses of the combined 12-month and 8-month data sets (C-FULCO in Table 4.18).

The *a*- and *b*-values from the Gutenberg-Richter analyses are not too meaningful as the time spans for the data sets are not the same. Normalising hazard parameters by the time spans are done in the estimations of probabilities of occurrence (Tables 4.16 and 4.17) and by normalising the Potential Damage Area (Table 4.18). The differences in probabilities of occurrence shown in Tables 4.16 and 4.17 are small. For example: for 11-day fortnight the probability of occurrence of a moment magnitude 2.0 or greater event in one month is 32% while for FULCO it is 38%. The comparable probabilities for moment magnitude events greater than 2.5 per year is 62% for 11-day fortnight and 60% for FULCO. In terms of the relatively poor Gutenberg-Richter statistics (Figure 4.24 shows that the amount of data is not quite sufficient for reliable statistical analyses) the above difference are clearly not significant. The increased stiffness response during the latter part of FULCO does, however, increase the strong ground motion hazard. The PDA/month increases from 16.6 during 11-day fortnight operations to 26.1 for FULCO.

4.3.3. Discussion

Case C was described here mainly to show the potentially hazardous effects of poor control on time of blasting and possibly other activities that cause an unfavourable time of day distribution of seismicity. In this case the stiffening of the system response described above may have added to this. Simple regular time of day statistics should always be kept to detect anomalous activity and analyses should be done to establish whether particular unfavourable activity could be the result of specific mining procedures.

The increased strong ground motion hazard indicated by the increased PDA is interesting. The inference is that an increased mining rate increases the stiffness response and the general stress drop associated with seismic events, increasing the hazard. In this case the statistics are not based on sufficient data, however, to warrant definitive conclusions.

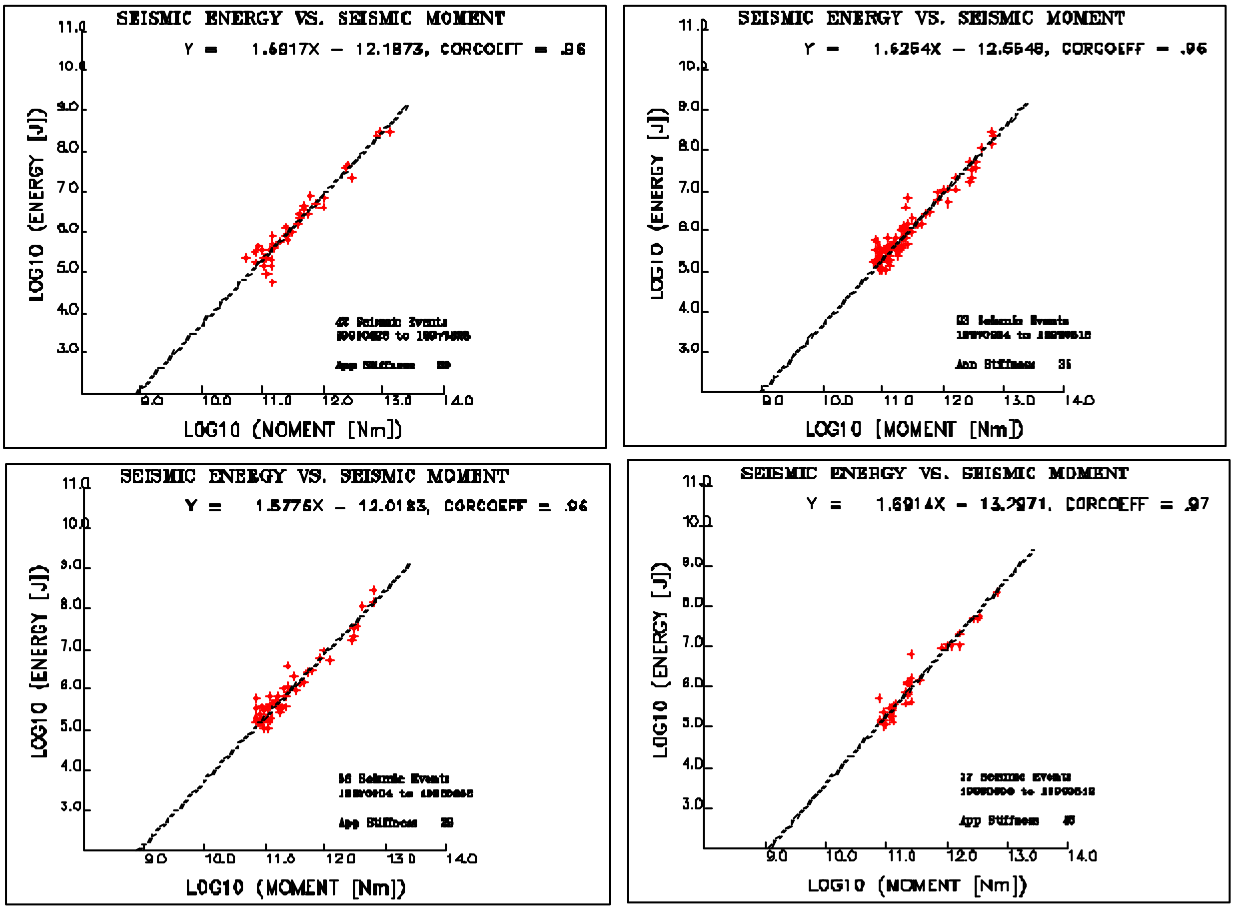

Figure 4.23. E-M plots for Case C. Top left represents 16 months of 11-day fortnight operations. Bottom left represents 12 months of FULCO, followed by a further 8 months of FULCO (bottom right). Top right represents all 20.5 months of FULCO

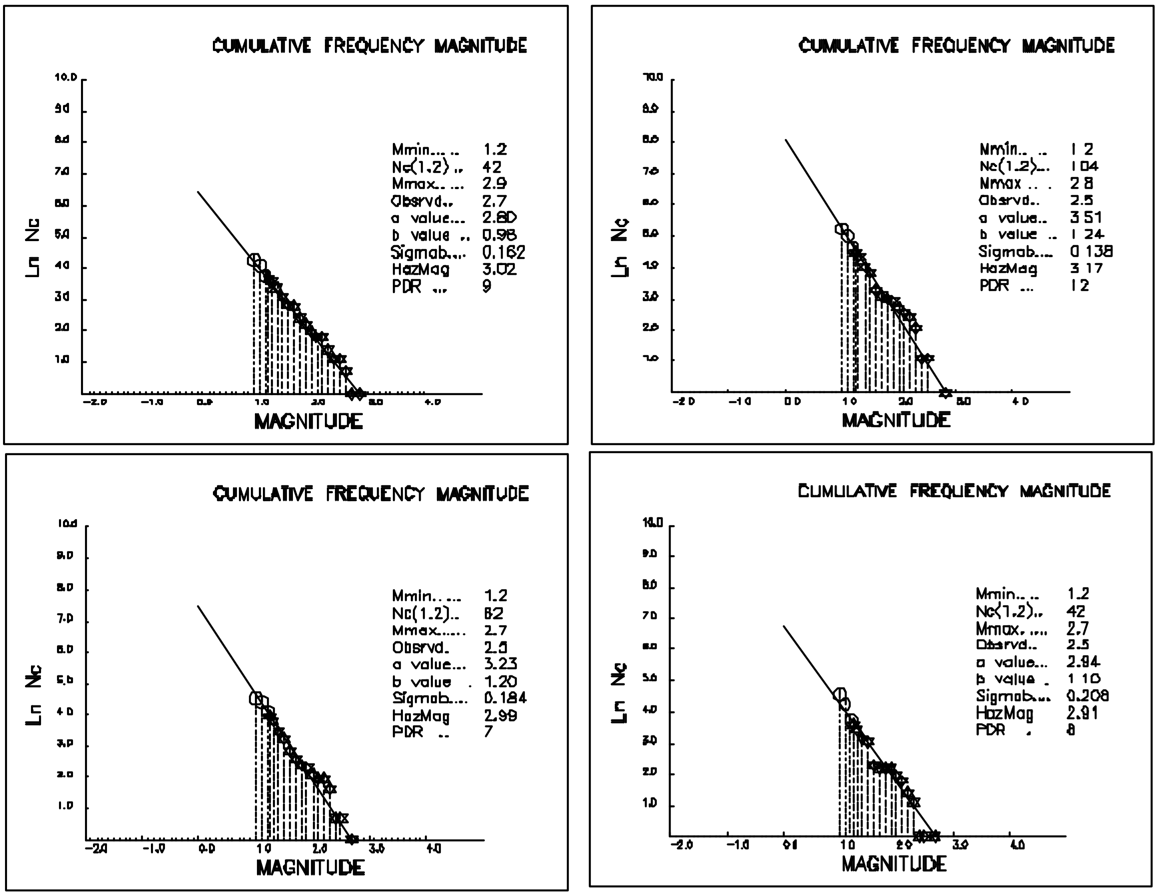

Figure 4.24. Gutenberg-Richter plots (moment magnitude) for Case C. The sequence is the same as for Fig. 4.23.

Table 4.16. Probability table for 11-day fortnight operations
Moment magnitude - Case C

```
PROBABILITY OF OCCURRENCE OF A SEISMIC EVENT WITH MAGNITUDE
NOT SMALLER THAN M  GIVEN TIME t AND T(M) - MEAN RECURRENCE
TIME FOR EVENTS WITH MAGNITUDES NOT SMALLER THAN M.

             (time in months)

Observation period in months =            15.8
Mmin                         =             1.2
Mmax                         =             2.9
Mmax observed                =             2.7
Delta M                      =             .10
Beta                         =            2.26
b-value                      =             .98
Total number of events       =              69
N events with M>=Mmin        =              42
Hazard Magnitude             =            3.02
Hazard Magnitude per year    =            2.94
SumMo from freq-mag relation =         .33E+14
SumE  from freq-mag relation =         .81E+09
Radius of potential damage   =             9.2
Area   of potential damage   =             266
```

RECCURRENCE TIMES AND EVENTS PER MONTH

M	.50	1.00	1.50	2.00	2.50	3.00
T(M)	.076	.237	.757	2.607	12.469	*******
T obs	.2286	.2286	.7170	2.2533	5.2577	*******
N(M)	207.8	66.5	20.8	6.1	1.3	.0
N obs	69	69	22	7	3	0

t	PROBABILITY OF OCCURRENCE					
1.0	1.0000	.9837	.7360	.3236	.0788	.0000
2	1.0000	.9996	.9275	.5408	.1512	.0000
3	1.0000	1.0000	.9793	.6872	.2178	.0000
4	1.0000	1.0000	.9939	.7862	.2790	.0000
5	1.0000	1.0000	.9981	.8534	.3354	.0000
6	1.0000	1.0000	.9994	.8991	.3873	.0000
7	1.0000	1.0000	.9998	.9304	.4350	.0000
8	1.0000	1.0000	.9999	.9518	.4789	.0000
9	1.0000	1.0000	1.0000	.9665	.5194	.0000
10	1.0000	1.0000	1.0000	.9767	.5566	.0000
11	1.0000	1.0000	1.0000	.9837	.5909	.0000
12	1.0000	1.0000	1.0000	.9886	.6225	.0000

***

Table 4.17a. Probability table for FULCO - Moment magnitude - Case C - total period

PROBABILITY OF OCCURRENCE OF A SEISMIC EVENT WITH MAGNITUDE NOT SMALLER THAN M GIVEN TIME t AND T(M) - MEAN RECURRENCE TIME FOR EVENTS WITH MAGNITUDES NOT SMALLER THAN M.

(time in months)

Observation period in months	=	20.5
Mmin	=	1.2
Mmax	=	2.8
Mmax observed	=	2.5
Delta M	=	.10
Beta	=	2.86
b-value	=	1.24
Total number of events	=	186
N events with M>=Mmin	=	104
Hazard Magnitude	=	3.17
Hazard Magnitude per year	=	3.01
SumMo from freq-mag relation	=	.42E+14
SumE from freq-mag relation	=	.92E+09
Radius of potential damage	=	11.7
Area of potential damage	=	432

RECCURRENCE TIMES AND EVENTS PER MONTH

M	.50	1.00	1.50	2.00	2.50	3.00
T(M)	.027	.111	.471	2.118	13.185	*******
T obs	.1103	.1103	.4460	1.3679	6.8393	*******
N(M)	773.9	184.9	43.6	9.7	1.6	.0
N obs	186	186	46	15	3	0

t	PROBABILITY OF OCCURRENCE					
1.0	1.0000	.9998	.8803	.3785	.0737	.0000
2	1.0000	1.0000	.9851	.6129	.1419	.0000
3	1.0000	1.0000	.9981	.7583	.2050	.0000
4	1.0000	1.0000	.9997	.8488	.2635	.0000
5	1.0000	1.0000	1.0000	.9053	.3176	.0000
6	1.0000	1.0000	1.0000	.9405	.3677	.0000
7	1.0000	1.0000	1.0000	.9625	.4141	.0000
8	1.0000	1.0000	1.0000	.9764	.4571	.0000
9	1.0000	1.0000	1.0000	.9851	.4969	.0000
10	1.0000	1.0000	1.0000	.9905	.5337	.0000
11	1.0000	1.0000	1.0000	.9940	.5678	.0000
12	1.0000	1.0000	1.0000	.9962	.5994	.0000

Table 4.17b. Probability table for FULCO - Moment magnitude - Case C - 8 month period

PROBABILITY OF OCCURRENCE OF A SEISMIC EVENT WITH MAGNITUDE NOT SMALLER THAN M GIVEN TIME t AND T(M) - MEAN RECURRENCE TIME FOR EVENTS WITH MAGNITUDES NOT SMALLER THAN M.

(time in months)

Observation period in months	=	8.5
Mmin	=	1.2
Mmax	=	2.7
Mmax observed	=	2.5
Delta M	=	.10
Beta	=	2.53
b-value	=	1.10
Total number of events	=	95
N events with M>=Mmin	=	42
Hazard Magnitude	=	2.91
Hazard Magnitude per year	=	3.01
SumMo from freq-mag relation	=	.41E+14
SumE from freq-mag relation	=	.96E+09
Radius of potential damage	=	8
Area of potential damage	=	209

RECCURRENCE TIMES AND EVENTS PER MONTH

M	.50	1.00	1.50	2.00	2.50	3.00
T(M)	.034	.121	.446	1.832	14.830	*******
T obs	.0896	.0896	.4054	1.2163	8.5140	*******
N(M)	252.3	70.4	19.1	4.6	.6	.0
N obs	95	95	21	7	1	0

t	PROBABILITY OF OCCURRENCE					
1.0	1.0000	.9996	.8933	.4261	.0667	.0000
2	1.0000	1.0000	.9873	.6683	.1288	.0000
3	1.0000	1.0000	.9983	.8069	.1867	.0000
4	1.0000	1.0000	.9998	.8869	.2406	.0000
5	1.0000	1.0000	1.0000	.9333	.2909	.0000
6	1.0000	1.0000	1.0000	.9604	.3378	.0000
7	1.0000	1.0000	1.0000	.9763	.3816	.0000
8	1.0000	1.0000	1.0000	.9858	.4223	.0000
9	1.0000	1.0000	1.0000	.9914	.4604	.0000
10	1.0000	1.0000	1.0000	.9948	.4959	.0000
11	1.0000	1.0000	1.0000	.9968	.5289	.0000
12	1.0000	1.0000	1.0000	.9980	.5598	.0000

Table 4.18. Summary of G-R and E-M statistics for Case C

E-M Statistics

	d-slope	c_value	Ap.Stiff[MPa]	App.Str.L[KPa]
C-11DFRT	1.592	-12.187	30.35	252.93
C-FUL0897	1.577	-12.018	29.23	258.52
C-FUL0599	1.691	-13.297	46.64	273.15
C-FULCO	1.625	-12.555	35.67	264.25

G-R stats - mom-mag

	b-val	Mmin	Mmax	Hazmag	PDA	PDA/month
C-11DFRT	0.98	1.2	2.86	2.94	266	16.63
C-FUL0897	1.20	1.2	2.69	2.99	163	13.58
C-FUL0599	1.10	1.2	2.68	3.01	209	26.13
C-FULCO	1.24	1.2	2.83	3.01	432	21.60

4.4. Case study D

A second case study in the Klerksdorp gold field yielded somewhat different results than that of case C. Here the period of FULCO mining for which data was obtained spans nearly two years, while data for the previous 17 months of 11-day fortnight operations was acquired. Like in the case of Case study C, the mining method was 'scattered'. The initial time of day distribution appears equally 'scattered', the reason for which is not clear. The production system apparently matured during the FULCO phase since the centares per month were higher (by 1.38 times) and the seismicity had settled into a more regular time of day distribution (see below).

The size distribution of seismic events is 'polarised' in the sense that three different populations, as described for Case A, can be distinguished. For the Gutenberg-Richter statistics emphasis was placed on the larger events.

Here again a particularly strong 'off shift' activity indicates early morning blasting, increasing the SE. This case is further used to show how the SE can be improved by small changes in shift scheduling.

4.4.1. Seismic Exposure Analysis

The details of the time of day distribution of seismicity and underground workers are tabulated in Tables 4.19 and 4.20 and graphically displayed in Figs. 4.25 to 4.29.

We note a rather random time of day distribution during the 11-day fortnight period. This randomness makes way for a much more ordered distribution during the FULCO period. During the FULCO period, there is, however, a peak in seismic activity during the two hours after midnight, clearly the effect of some blasting activity. The resulting time of day distribution of events > magnitude 2 is quite unfavourable. -see Figure 4.29

Early blasting while workers are still underground causes another undesirable effect. This is shown by the increase in seismic activity during the 14^{th} hour, as indicated in Figure 4.26. Pro-rating the events emphasises the phenomenon (Figure 4.28) because of the occurrence of larger events during this hour (Figure 4.29). To illustrate the improvement in seismic exposure that can be brought about by relatively simple discipline (e.g. delaying the blast for say 30 minutes till the mine is completely cleared), the SE calculations were re-run with zero workers in the 14^{th} hour. The results, given in Table 4.22, show a significant improvement in SE. For the 11-day fortnight case, the SE/day drops from 99.5 to 86.7 and the pro-rated SE/centare drops from 5.7 to 4.6. For the FULCO case the numbers are 166 to 149 and 14.76 to 9.56 respectively.

Table 4.19. Time of day personnel distribution, frequency rates and seismic exposure for 11-day fortnight operations - Case D.

Hour of Day	N > 1.0	Avg. N > 1.0	Men exposed in prod. day	Hourly SE	Events >0.0 Prorated to 1.0	Avg. N Prorated	Hourly SE
1st	6	0.0155	233	3.60	143.09	0.3688	85.93
2nd	4	0.0103	233	2.40	16.82	0.0434	10.10
3rd	2	0.0052	233	1.20	11.95	0.0308	7.18
4th	8	0.0206	0	0.00	92.73	0.2390	0.00
5th	3	0.0077	544	4.21	43	0.1108	60.29
6th	4	0.0103	544	5.61	40.49	0.1044	56.77
7th	3	0.0077	544	4.21	13.87	0.0357	19.45
8th	4	0.0103	618	6.37	49.88	0.1286	79.45
9th	4	0.0103	618	6.37	21.06	0.0543	33.54
10th	4	0.0103	618	6.37	42.79	0.1103	68.16
11th	9	0.0232	618	14.34	83.63	0.2155	133.20
12th	9	0.0232	618	14.34	218.89	0.5641	348.64
13th	2	0.0052	618	3.19	152.32	0.3926	242.61
14th	8	0.0206	618	12.74	184.15	0.4746	293.31
15th	14	0.0361	0	0.00	194.33	0.5009	0.00
16th	16	0.0412	0	0.00	484.91	1.2498	0.00
17th	9	0.0232	0	0.00	168.73	0.4349	0.00
18th	7	0.0180	0	0.00	64.85	0.1671	0.00
19th	4	0.0103	0	0.00	114.14	0.2942	0.00
20th	5	0.0129	182	2.35	29.33	0.0756	13.76
21st	3	0.0077	182	1.41	53.57	0.1381	25.13
22nd	9	0.0232	233	5.40	48.26	0.1244	28.98
23rd	7	0.0180	233	4.20	69.45	0.1790	41.71
24th	2	0.0052	233	1.20	19.02	0.0490	11.42
Daily Totals:				99.50			1559.62
			Number of Production Days:		388		
			Total Number of Days:		512		

Table 4.20. Time of day personnel distribution, frequency rates and seismic exposure for FULCO operations - Case D

Hour of Day	N > 1.0	Avg. N > 1.0	Men exposed in prod. day	Hourly SE	Events >0.0 Prorated to 1.0	Avg. N Prorated	Hourly SE
1st	17	0.0438	191	8.37	140.21	0.3614	69.02
2nd	19	0.0490	191	9.35	238.47	0.6146	117.39
3rd	14	0.0361	191	6.89	143.45	0.3697	70.62
4th	12	0.0309	0	0.00	208.72	0.5379	0.00
5th	3	0.0077	506	3.91	41.41	0.1067	54.00
6th	9	0.0232	506	11.74	132.62	0.3418	172.95
7th	9	0.0232	506	11.74	119.63	0.3083	156.01
8th	8	0.0206	543	11.20	68.79	0.1773	96.27
9th	7	0.0180	543	9.80	60.37	0.1556	84.49
10th	9	0.0232	543	12.60	132.8	0.3423	185.85
11th	7	0.0180	543	9.80	351.38	0.9056	491.75
12th	8	0.0206	543	11.20	108.9	0.2807	152.40
13th	9	0.0232	506	11.74	351.45	0.9058	458.33
14th	13	0.0335	506	16.95	1149.74	2.9632	1499.40
15th	23	0.0593	0	0.00	1982.31	5.1090	0.00
16th	29	0.0747	0	0.00	1885.94	4.8607	0.00
17th	23	0.0593	0	0.00	1557.47	4.0141	0.00
18th	24	0.0619	0	0.00	755.66	1.9476	0.00
19th	22	0.0567	0	0.00	514.83	1.3269	0.00
20th	17	0.0438	181	7.93	517.39	1.3335	241.36
21st	18	0.0464	181	8.40	241.79	0.6232	112.79
22nd	12	0.0309	191	5.91	343.25	0.8847	168.97
23rd	10	0.0258	191	4.92	173.47	0.4471	85.39
24th	10	0.0195	191	3.73	72.22	0.1861	35.55
Daily Totals:				166.16			4252.57
			Number of Production Days:		707		
			Total Number of Days:		719		

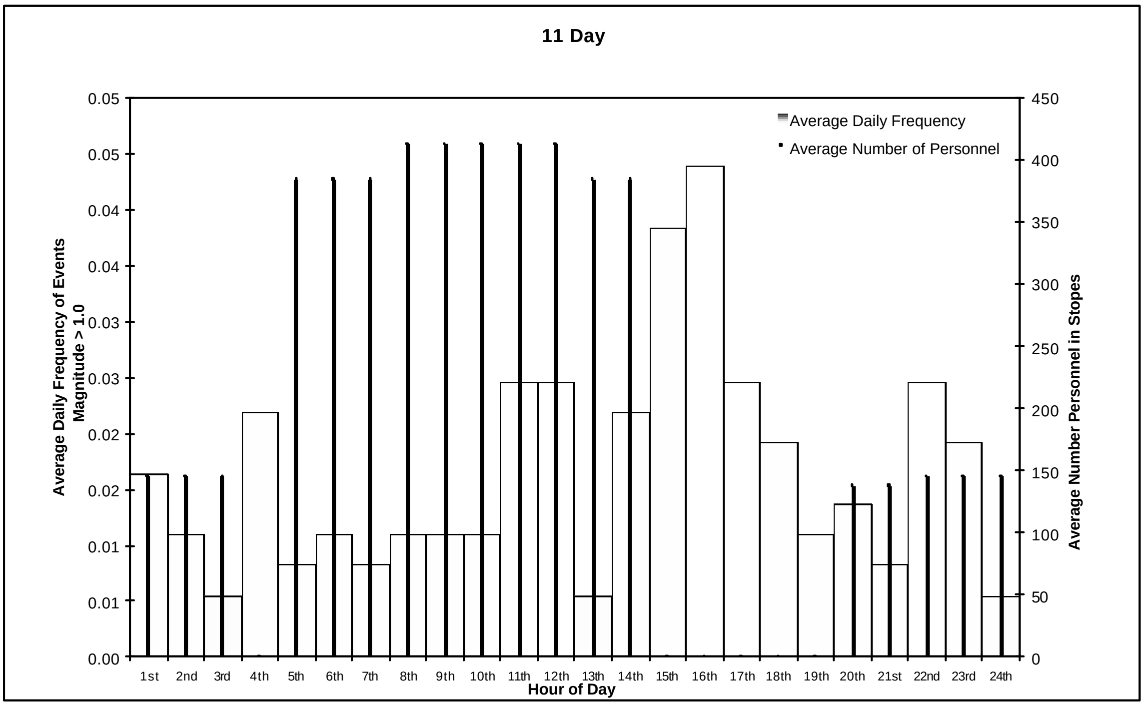

Figure 4.25. Time of day seismic distribution of seismic events > magnitude 1.0 and underground workers for the 11-day fortnight period - Case D

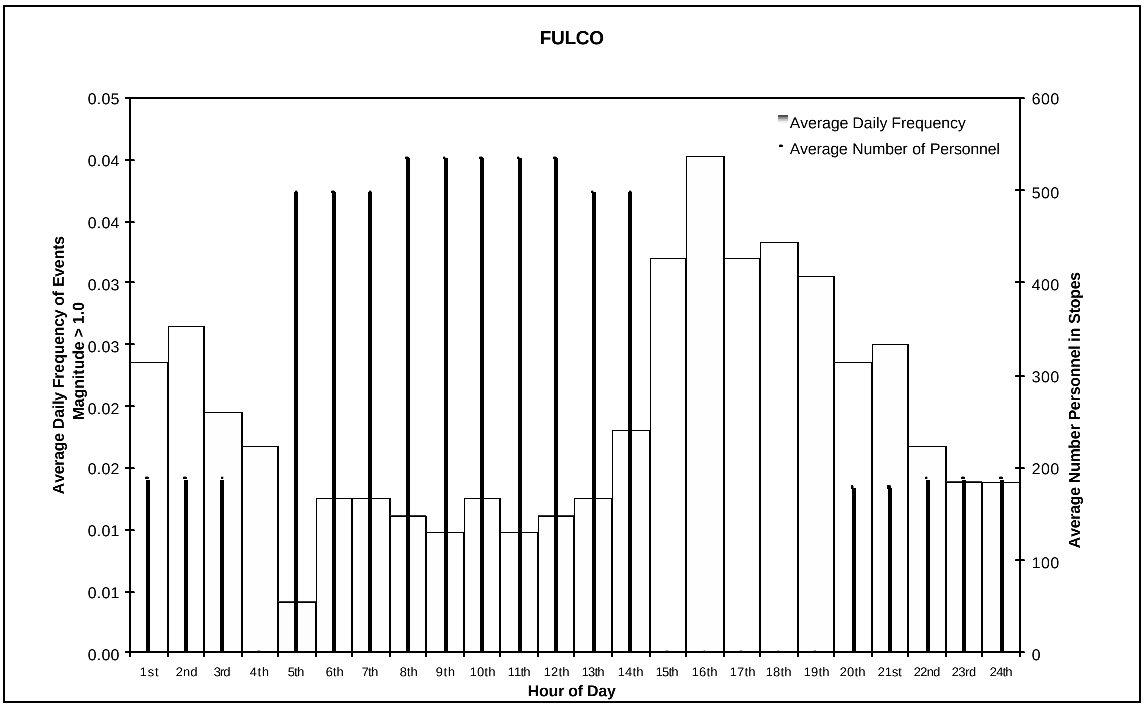

Figure 4.26. Time of day seismic distribution of seismic events > magnitude 1.0 and underground workers for the FULCO period - Case D

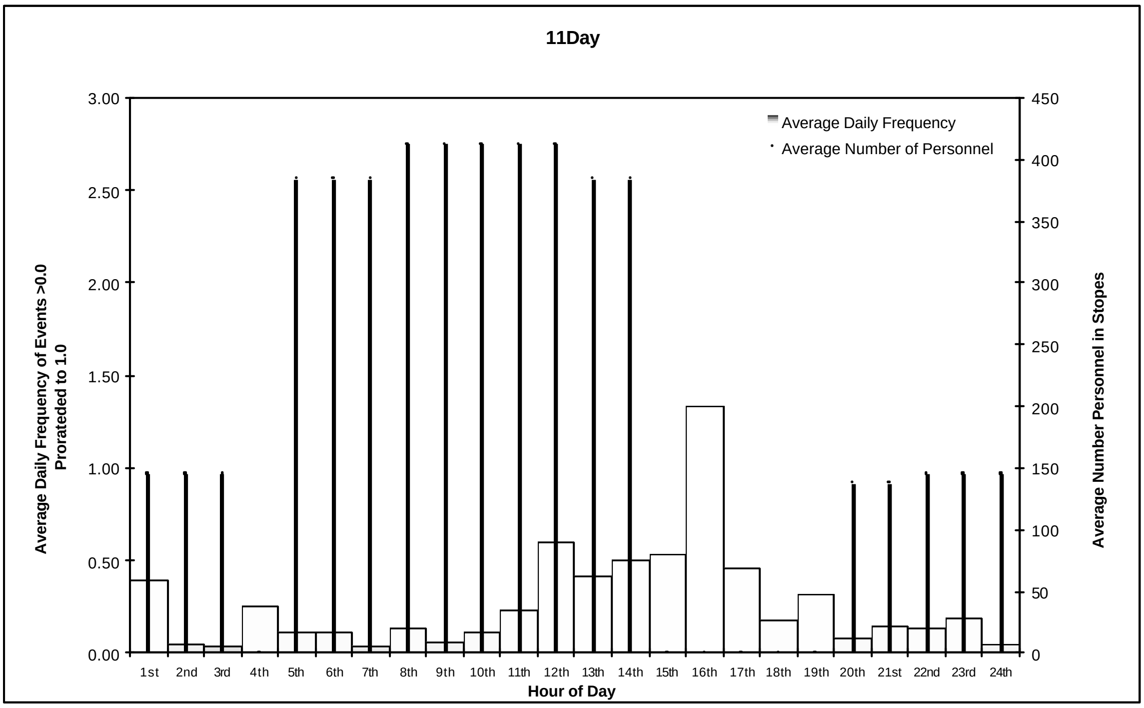

Figure 4.27. Time of day seismic distribution of seismic events > magnitude 0.0, pro-rated to magnitude 1.0, and underground workers for the 11-day fortnight period - Case D

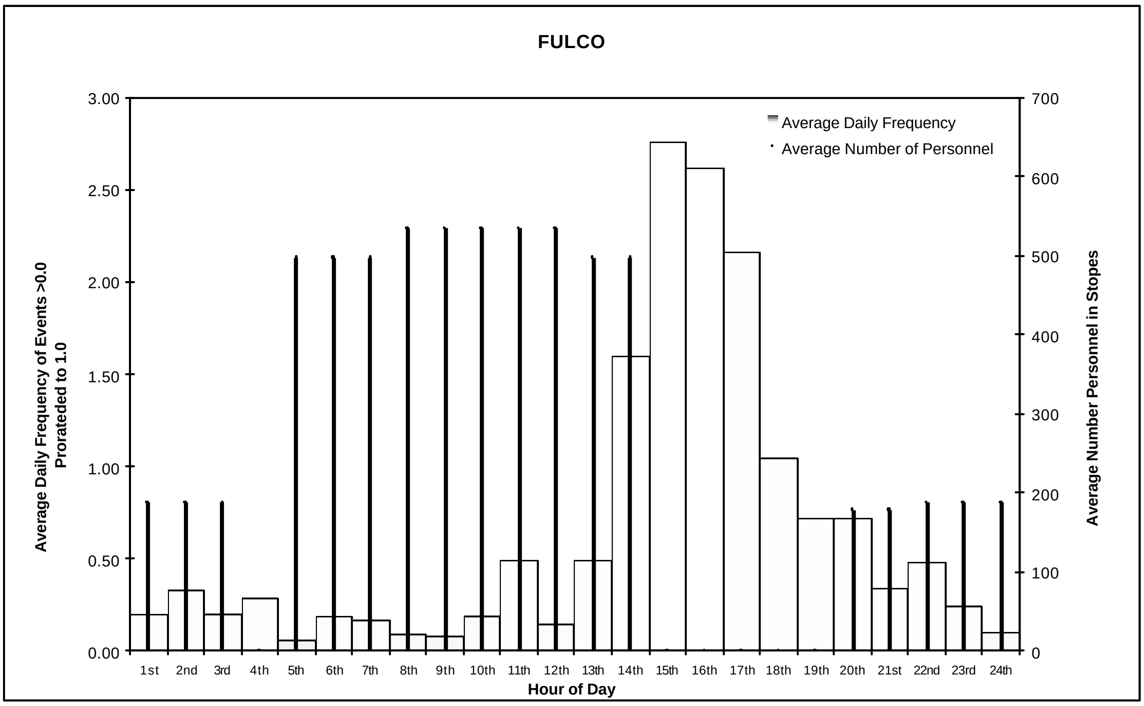

Figure 4.28. Time of day seismic distribution of seismic events > magnitude 0.0, pro-rated to magnitude 1.0, and underground workers for the FULCO period - Case D

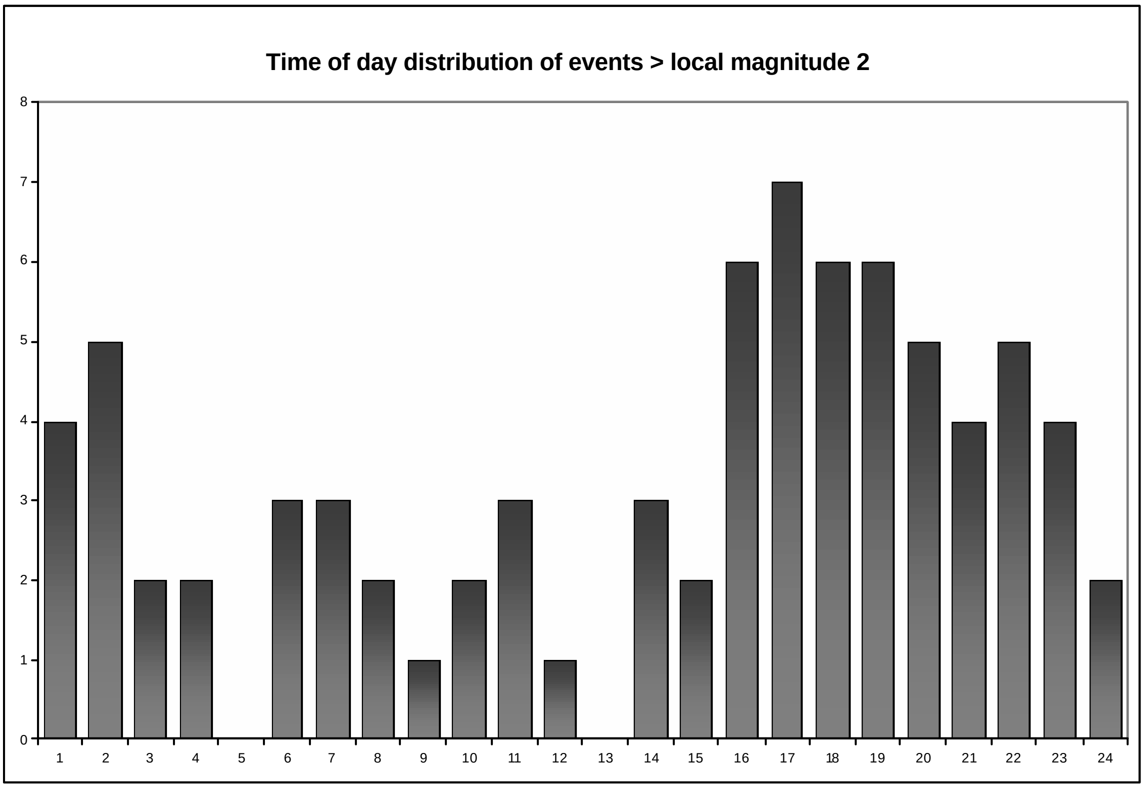

Figure 4.29. Time of day seismic distribution of seismic events > magnitude 2.0 for the FULCO period - Case D

Table 4.21. Summary of SE calculations - Case D

	11-day Fortnight	FULLCO
SE/day	99.50	166.16
SE/day prorated	1559.62	4252.57
N prod. Days	388	707
Centares produced	106574	203671
SE/centare	0.36	0.58
SE/centare prorated	5.68	14.76

Table 4.22. Summary of SE calculations for Case D - if no staff exposed during the14th hour.

	11-day Fortnight	FULLCO
SE/day	86.76	149.20
SE/day prorated	1266.31	2753.16
N prod. Days	388	707
Centares produced	106574	203671
SE/centare	0.32	0.52
SE/centare prorated	4.61	9.56

4.4.2. Gutenberg-Richter and E-M statistics

The Energy-Moment- and Gutenberg-Richter plots for the two data sets are given in Figure 4.30. The tri-modal size distribution seen in the 11-day fortnight data is accentuated in the FULCO data set. For the larger events, no equivalent patterns are shown in the E-M distribution, although it is well known that the very small events in this area do define a distinctly separate population on the E-M plot

The Gutenberg-Richter statistics are given in full in Tables 4.24 and4.25 while the E-M and G-R statistics are summarised in Table 4.23. From 11-day fortnight to FULCO there is a general increase in seismic hazard as indicated by increases in m_{max}, hazard magnitude and PDA. A general stiffening of the system is reflected by increases in the *d*-value and Apparent Stiffness and the *b*-value. A general increase in level of stress is indicated by the increase in Apparent Stress Level.

4.4.3. Discussion

Case D is the most successful case studied in terms of production gain. Normalised to time period, the FULCO yielded 8630 centares/month compared with the 11-day fortnight figure of 6323 centares/month. This gain was, however, associated with an increase in seismic hazard both in terms of a general hazard assessment as well as far as Seismic Exposure is concerned. Of particular concern is the occurrence of larger events on shift. relative numbers.

It is unknown what the cost associated with seismicity was for the mine at the time so it is unclear whether the financial gain through increased production warranted the increased seismic hazard.

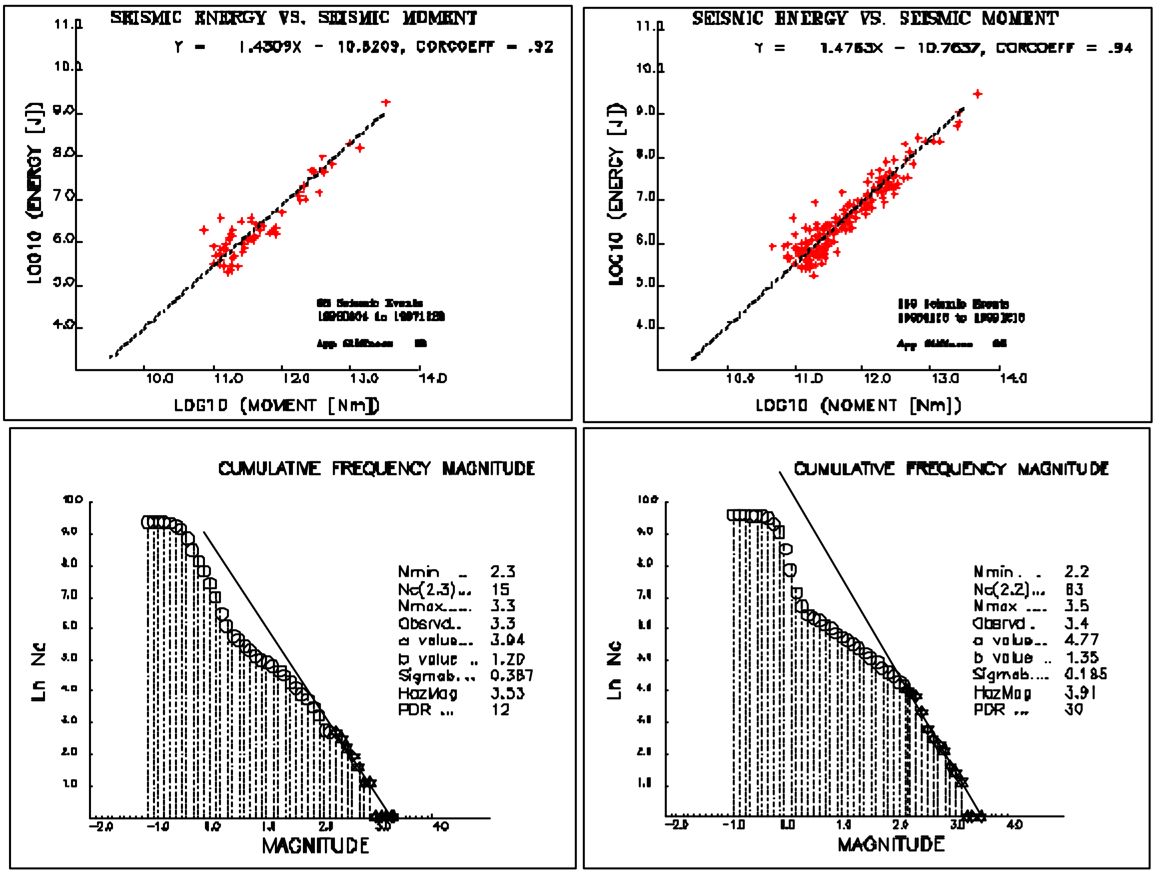

Figure 4.30 Gutenberg-Richter and Energy-Moment plots for 11-day fortnight operations (left) and FULCO (right) for Case D

Table 4.23. A summary of G-R and E-M statistics for Case D

	d-slope	c_value	Ap.Stiff[MPa]	App.Str.L[KPa]		
D-11DFOR	1.431	-10.321	18.13	237.68		
D-FULLCO	1.476	-10.764	25.41	283.41		
	b-val	Mmin	Mmax	Hazmag	PDA	PDR
D-11DFOR	1.20	2.30	3.28	3.53	444	11.89
D-FULLCO	1.35	2.20	3.53	3.91	2874	30.25

Table 4.24. Probability table for 11-day fortnight operations - Case D

```
PROBABILITY OF OCCURRENCE OF A SEISMIC EVENT WITH MAGNITUDE
NOT SMALLER THAN M  GIVEN TIME t AND T(M) - MEAN RECURRENCE
TIME FOR EVENTS WITH MAGNITUDES NOT SMALLER THAN M.

             (time in months)

Observation period in months =           17.1
Mmin                         =            2.3
Mmax                         =            3.3
Mmax observed                =            3.3
Delta M                      =            .10
Beta                         =           2.76
b-value                      =           1.20
Total number of events       =          11953
N events with M>=Mmin        =             15
Hazard Magnitude             =           3.53
Hazard Magnitude per year    =           3.44
SumMo from freq-mag relation =        .92E+14
SumE  from freq-mag relation =        .13E+10
Radius of potential damage   =           11.8
Area   of potential damage   =            444
```

RECCURRENCE TIMES AND EVENTS PER MONTH

M	.50	1.00	1.50	2.00	2.50	3.00
T(M)	.007	.029	.118	.479	2.094	13.683
T obs	.0525	.1112	.2314	.6850	1.9029	17.1260
N(M)	2322.0	582.4	145.5	35.7	8.2	1.3
N obs	326	154	74	25	9	1

t	PROBABILITY OF OCCURRENCE					
1.0	1.0000	1.0000	.9992	.8756	.3943	.0748
2	1.0000	1.0000	1.0000	.9803	.6275	.1437
3	1.0000	1.0000	1.0000	.9962	.7676	.2072
4	1.0000	1.0000	1.0000	.9992	.8530	.2657
5	1.0000	1.0000	1.0000	.9998	.9059	.3196
6	1.0000	1.0000	1.0000	.9999	.9390	.3694
7	1.0000	1.0000	1.0000	1.0000	.9600	.4153
8	1.0000	1.0000	1.0000	1.0000	.9735	.4576
9	1.0000	1.0000	1.0000	1.0000	.9822	.4967
10	1.0000	1.0000	1.0000	1.0000	.9880	.5329
11	1.0000	1.0000	1.0000	1.0000	.9918	.5663
12	1.0000	1.0000	1.0000	1.0000	.9943	.5971

Table 4.25 Probability table for FULCO - Case D

PROBABILITY OF OCCURRENCE OF A SEISMIC EVENT WITH MAGNITUDE NOT SMALLER THAN M GIVEN TIME t AND T(M) - MEAN RECURRENCE TIME FOR EVENTS WITH MAGNITUDES NOT SMALLER THAN M.

(time in months)

Observation period in months	=	23.6
Mmin	=	2.2
Mmax	=	3.5
Mmax observed	=	3.4
Delta M	=	.10
Beta	=	3.11
b-value	=	1.35
Total number of events	=	15023
N events with M>=Mmin	=	63
Hazard Magnitude	=	3.91
Hazard Magnitude per year	=	3.74
SumMo from freq-mag relation	=	.24E+15
SumE from freq-mag relation	=	.56E+10
Radius of potential damage	=	30.2
Area of potential damage	=	2874

RECCURRENCE TIMES AND EVENTS PER MONTH

M	1.00	1.50	2.00	2.50	3.00	3.50
T(M)	.009	.042	.200	.977	5.483	216.268
T obs	.0683	.1305	.2715	.8436	4.7244	*******
N(M)	2667.6	563.0	118.2	24.2	4.3	.1
N obs	346	181	87	28	5	0

t	PROBABILITY OF OCCURRENCE					
1.0	1.0000	1.0000	.9925	.6435	.1689	.0047
2	1.0000	1.0000	.9999	.8708	.3089	.0093
3	1.0000	1.0000	1.0000	.9524	.4250	.0140
4	1.0000	1.0000	1.0000	.9822	.5214	.0186
5	1.0000	1.0000	1.0000	.9933	.6014	.0232
6	1.0000	1.0000	1.0000	.9974	.6679	.0278
7	1.0000	1.0000	1.0000	.9990	.7231	.0323
8	1.0000	1.0000	1.0000	.9996	.7690	.0369
9	1.0000	1.0000	1.0000	.9998	.8072	.0414
10	1.0000	1.0000	1.0000	.9999	.8390	.0459
11	1.0000	1.0000	1.0000	1.0000	.8655	.0503
12	1.0000	1.0000	1.0000	1.0000	.8876	.0548

5. Seismic hazard after breaks in a production cycle

5.1. Introduction

Observations suggest that seismic hazard is higher during the first full shift after a period of no mining, e.g. after weekends.

The objective of the investigation was to quantify the difference in seismic hazard for a weekly production shift day and the production shift after a break in production. This involved the evaluation of the difference in seismic hazard for example on Mondays compared to other days. The data was analysed in sufficient detail to also capture the effects of a break in production at any time of the week.

Seismic hazard comparison was done by obtaining Cumulative-Frequency magnitude statistics for seismic data associated the first shift after off-weekends, which can then be compared with that of all data for the whole mine.

5.2. Methodology

5.2.1. Establishing the daily time of blasting

It has been observed that seismic activity (numbers of events per unit time) increases for the period that follows after blasting. The times of blasting can be identified by stacking the data from a seismic catalogue on a daily basis for defined intervals. Special software, based on work done for GAP303, namely *BLASTIME* , was used to perform this task.

The functionality of BLASTIME can be described as follows:

Any reasonable time interval (i.e., step, or increment) of counting Δt; e.g., 1 hr, 30 min, 15 min etc. can be defined. The number of intervals *n* in which the data is stacked is then 24 hours/Δt. For the interval (t_i, t_{i+1}) the total number of events, total energy and total moment is denoted by N_i *(i.e.,* $SN_I = N^{tot}$, i=1...n*),* E_i and M_i respectively. The total number of events in a catalogue is denoted by N^{tot} while the sum of moment and energy for the catalogue is denoted by M^{tot} and E^{tot}*,* respectively*.*

Three types of so-called ‘blasting ratios’ can be used to identify the blasting period by comparing a specific parameter for the interval to the total parameter value for the catalogue. The ratios per interval are:

- Seismic activity ratio: $(RN)_i = \Sigma N_I / N^{tot}$,
- Seismic moments ratio, $(RM)_I = (\Sigma M)_I / M^{tot}$
- Seismic energies ratio, $(RE)_I = (\Sigma E)_I / E^{tot}$

It is useful to express these ratios in percentage of total number of events, total sum of moments, or total sum of energies, respectively. Peaks in these ratios are likely to indicate the times of blasting. It should be noted that RM_i and RE_i could also tend to become large when an event with a single large radiated energy or moment value occurs in the interval *i*. RN_i does not suffer from this effect, but it reflects only numbers of events, without any reference to their source characteristics. Thus it should be noted that if only RM_i and/or RE_i are large for a given interval, but RN_i is small, most likely one or a few large events cause this effect, and not blasting activities.

Table 5.1 Example output from BLRATIO

DATE	DAY	DAILY NUM	BLAST NUM	NO-BL NUM	RATES RATIO	MOMENT RATIO	ENERGY RATIO
19990101	1	11	2	9	1.56	0.05	0.04
19990102	2	9	1	8	0.88	0.06	0.08
19990103	3	8	0	8	0.00	0.00	0.00
19990104	4	89	66	23	20.09	0.11	0.61
19990105	5	59	37	22	11.77	0.79	1.29
19990106	6	110	74	36	14.39	2.38	1.00
19990107	7	73	40	33	8.48	0.19	0.19
19990108	8	68	42	26	11.31	0.23	0.01
19990109	9	22	5	17	2.06	0.10	0.07
19990110	10	13	3	10	2.10	0.02	0.00
19990111	11	22	7	15	3.27	4.24	7.60
19990112	12	54	41	13	22.08	0.16	0.26
19990113	13	49	19	30	4.43	7.67	4.76
19990114	14	67	49	18	19.06	539.13	3041.82
...							

Table 1: Example output of blratio

The BLASTIME algorithm does not require that blasting occurs every day but the times of blasting should be fairly consistent. The method is not sensitive to small shifts in time of blasting, but drastic changes, especially if they are erratic, will render this method useless. In a further refinement, it is possible to group the data by days of the week, and identify some differences in blasting times (e.g., on Saturday and Sunday versus the rest of the week). Consistency in such deviations is still required, for blasting times to be properly identified by the technique.

5.2.2. Identifying breaks in production

Once the blast times have been inferred from the whole seismic catalogue with BLASTIME, the production/blasting days in a catalogue can be determined. Although blasting is not done every day for all panels, one can still identify the production shifts by considering the events that occur during blasting time for the whole mine. Breaks in production can be associated with periods where blasts were absent. The program used for this analysis is called *BLRATIO [Eneva].*

Let the usual blasting time period be denoted by $[(tb)_1, (tb)_2]$. Then, for any given day, the number of events in the blasting period, say n_b, can be counted and compared to the number of events from the remaining times, $[0{:}00, (tb)_1)$ and $((tb)_2, 24{:}00)$, say n_{nob}. For every day sums of moments and energies can be calculated, and denoted by $(\Sigma M)_b$ and $(\Sigma E)_b$ for the blasting time and $(\Sigma M)_{nob}$ and $(\Sigma E)_{nob}$, for the remaining time. Let the length in hours of the blasting period be denoted by $(\delta t)_b = (tb)_2 - (tb)_1$, and the length of the remaining time with $(\delta t)_{nob} = ((tb)_1 - 0h00) + (24h00 - (tb)_2)$. Then, it is useful to construct the following ratios on a daily basis for the whole catalogue:

$$DRN = \frac{n_b}{(dt)_b} : \frac{n_{nob}}{(dt)_{nob}}; \; DRM = \frac{(\Sigma M)_b}{(dt)_b} : \frac{(\Sigma M)_{nob}}{(dt)_{nob}}; \; DRE = \frac{(\Sigma E)_b}{(dt)_b} : \frac{(\Sigma E)_{nob}}{(dt)_{nob}}$$

In these ratios, hourly quantities measured from the usual times of blasting are compared with the same quantities measured from the remaining times. Thus, if there has been blasting on a given day, all ratios will exceed 1 significantly. As before, large *DRM* and *DRE*, but small *DRN,* indicate the occurrence of isolated large events rather than increased seismic activity associated with blasting.

Table 1 shows an example of the output from BLRATIO. The program also outputs the number of events occurring during blasting time, for each day in the catalogue.

A graph of the daily blasting events is shown below and can be used to identify non-working days. Figure 5.1 shows an example of events that occurred during blasting time over a period of 2 months. The absence of seismicity on weekends during the usual (weekly) blasting hours can be seen and is indicated with the horizontal bars at the base of the bar chart.

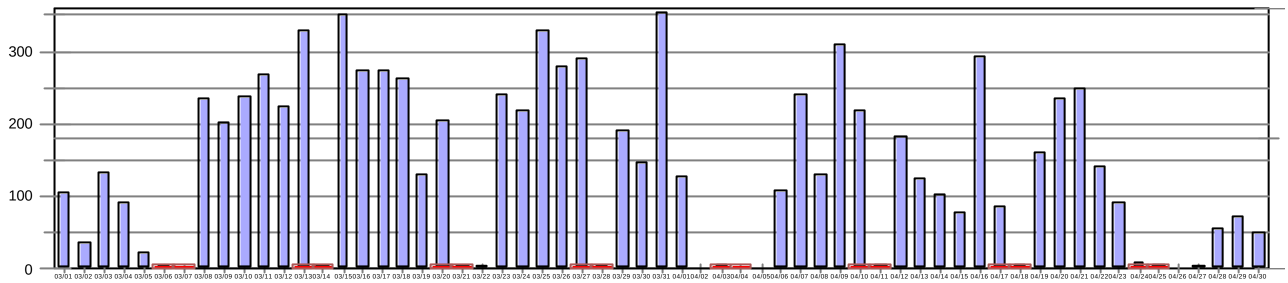

Figure 5.1. Frequency distribution of events during blast time. Breaks in production (absence of blasting e.g. non-production weekends)are indicated with the red bars.

5.2.3. Extracting seismic data

A program called *separat4* [Van Aswegen] is used to extract seismic data from the seismic catalogue over specified time-periods. The outputs from the programs BLASTIME and BLSPLIT were used to define periods of production as well as breaks in production, in that way creating a subset from the original seismic catalogue, representing only days following breaks. .

5.2.4. Comparison of Cumulative Frequency-magnitude with all data

A standard Gutenberg-Richter analysis can now be performed for the data set from periods after breaks vs. the data set for all times. The traditional way to quantify seismic hazard is to determine the projected m_{max} from the linear fit to the data set. However, a more advanced parameter, *Hazard Magnitude* (see GAP303), takes into account the cumulative hazard posed by events of cumulative magnitudes between magnitude 1 and m_{max}. For example, it can be expected that a relatively high number of events between Mag 1.0 and 1.5, also contribute to the overall seismic hazard, and not only the largest possible event. The Hazard magnitude is based on the sum of seismic moment and/or energy (depending on the magnitude equation) interpreted to be associated with all events between magnitude 1 and m_{max}. This sum may be normalised for by the time period to express the seismic hazard in terms of the sum - and hence the hazard magnitude - per year.

Because of the time-normalisation, it is required to supply the correct time period for the data subset of that belonging to breaks in production.

5.3. Case study E - hazard after production breaks - a Free State example

Case E is from a scattered mining operation mine in the Free State gold field.

During 1999, a few large events that occurred after breaks in production resulted in a perception that the mine is more hazardous after long break in production. A magnitude 3.2 event occurred on 8 January 1999, i.e. almost immediately after mining commenced after the Christmas break. Easter weekend represented a break of 4 days (2nd to 5th of April), after which a number of large events also followed. Three events of magnitude order 2 followed on the 7th and 8th of April.

BLASTIME determined the blasting period as from 14:00 to 17:00, and a total of 20 break days were identified with BLRATIO, including 2 day weekends and long weekends. (For example, if 20 January 1999 is the first day after the break, then the hazard period is taken from 19 January 21:00, to 21 January 14:00. The hazard period was taken to be a time period of 41 hours.)

Figure 5.2 (on the left) shows the Frequency-Magnitude distribution for Case E, for the entire catalogue of seismic data for 1999. The Frequency-Magnitude distribution is also shown (on the right) for the seismicity associated with the period after each non-production period for all such periods. The seismic catalogue has a projected m_{max} of 3.7 (the observed max was 3.4), with a Hazard magnitude of 3.86. For the data from the period after the break, an m_{max} of 2.5 was calculated (observed max is 2.2), with a Hazard magnitude of 3.23. It should be noted that the Hazard magnitude is normalised for one year, hence the higher value than m_{max}.

Probability tables which show the probability for events of a specified magnitude to occur within a specified time period is also given as Tables 5.2 and 5.3.

5.4. Case study F - hazard after production breaks - a Far West Rand example.

Case F is from a longwall mining operation in the Far West Rand

BLASTIME and BLASTRATIO identified a total of 11 non-production periods. From the time-of-day distribution the blasting time was determined as starting at 11:00 and ending at 20:00. The analysis period (after the break in production) was taken from 21:00 on the last day of the non-production period to 12:00 two days after. The statistical hazard of the combined seismicity of all such periods was then compared to the hazard of the complete seismic catalogue for 1998.

A m_{max} of 3.9 was calculated for the 1998 seismic catalogue, with a Hazard magnitude of 4.32, as shown in Figure 5.4. For the seismic data (see above for times) after a non-production period a m_{max} of 3.0 was found, with a Hazard magnitude of 4.01.

5.5. Quantitative seismic hazard comparison

The analyses described above are of a statistical nature. To test the hazard on days following breaks in production in a quantitative way, the following simple analysis was done: The sums of seismic moment for the data in the subsets were divided by the total time spans represented by the subsets. The same was done for the full data sets, yielding 'sum of moment per month' values for each data set. The results are as follows:

Data set	Σ moment [N.m]	Time span [months]	Moment/month
Case E - full data set	4.589255E14	11.5	3.990E13
Case E - after breaks	1.398730E13	01.1	1.270E13
Case F - full data set	1.305931E15	12.0	1.088E14
Case F - after breaks	3.114909E13	00.5	5.230E13

In terms of this analysis, there is clearly no increase in seismic hazard associated with days after breaks in production.

5.6. Conclusions

The seismic catalogues from two mines were investigated. Hazard of the catalogue for a year of seismic data was compared with the hazard of the dataset comprising all periods following on a break in production for that year. For both areas the Hazard magnitude was found to be lower for the seismicity associated with the period following on the break in production. Hazard magnitude, based on a time normalised, statistical sum of moment and energy, is considered a reasonable parameter to compare the hazard for the different populations. There is no indication, therefore, that the day after a break in production is more hazardous than any other day.

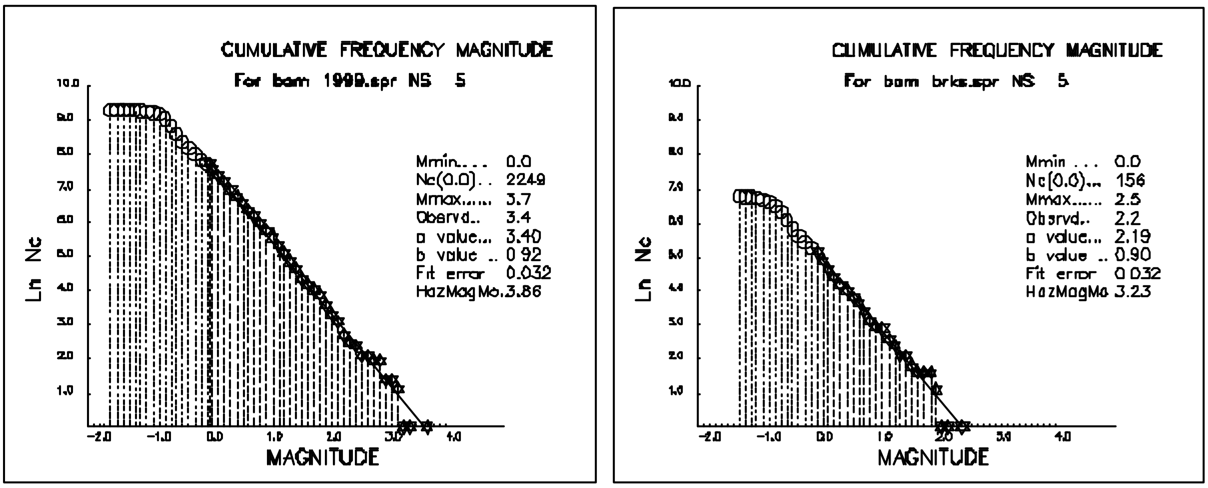

Figure 5.2. Gutenberg-Richter plot for seismic data from Case study E (left) and for the subset of events which occurred during production days following breaks.

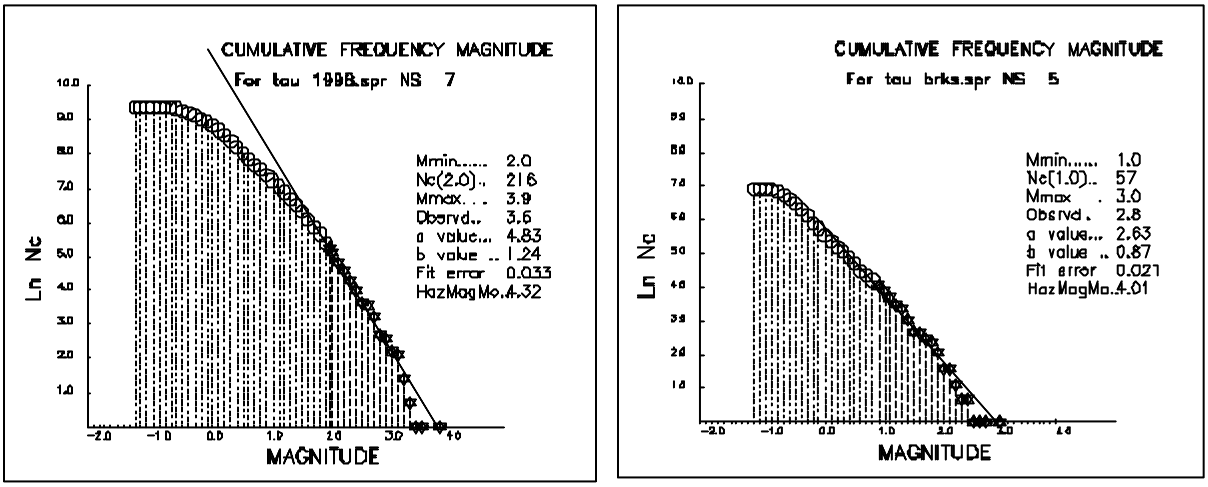

Figure 5.3. Gutenberg-Richter plot for seismic data from Case study F (left) and for the subset of events which occurred during production days following breaks.

Table 5.2. Probability table for Case E - normal seismic catalogue.

PROBABILITY OF OCCURRENCE OF A SEISMIC EVENT WITH MAGNITUDE NOT SMALLER THAN M GIVEN TIME t AND T(M) - MEAN RECURRENCE TIME FOR EVENTS WITH MAGNITUDES NOT SMALLER THAN M.

(time in months)

Observation period in months	=	11.5
Mmin	=	.0
Mmax	=	3.7
Mmax observed	=	3.4
Delta M	=	.10
Beta	=	2.12
b-value	=	.92
Total number of events	=	10882
N events with M>=Mmin	=	2249
Hazard magnitude1	=	3.86
Hazard magnitude3	=	3.85
Sum of moment from haz_mag1	=	.48E+15
Sum of energy from haz_mag1	=	.10E+11

RECCURRENCE TIMES AND EVENTS PER MONTH

M	1.00	1.50	2.00	2.50	3.00	3.50
T(M)	.043	.124	.364	1.109	3.833	25.628
T obs	.0365	.1070	.3182	1.0413	2.8635	*******
N(M)	269.1	92.6	31.5	10.3	3.0	.4
N obs	314	107	36	11	4	0

t	PROBABILITY OF OCCURRENCE					
1.0	1.0000	.9997	.9361	.5941	.2297	.0383
2	1.0000	1.0000	.9959	.8352	.4067	.0751
3	1.0000	1.0000	.9997	.9331	.5429	.1105
4	1.0000	1.0000	1.0000	.9728	.6479	.1446
5	1.0000	1.0000	1.0000	.9889	.7288	.1773
6	1.0000	1.0000	1.0000	.9955	.7910	.2088
7	1.0000	1.0000	1.0000	.9982	.8390	.2391
8	1.0000	1.0000	1.0000	.9993	.8760	.2682
9	1.0000	1.0000	1.0000	.9997	.9044	.2962
10	1.0000	1.0000	1.0000	.9999	.9264	.3232
11	1.0000	1.0000	1.0000	.9999	.9433	.3491
12	1.0000	1.0000	1.0000	1.0000	.9563	.3740

Table 5.3. Probability table for Case E - events after break in production

PROBABILITY OF OCCURRENCE OF A SEISMIC EVENT WITH MAGNITUDE NOT SMALLER THAN M GIVEN TIME t AND T(M) - MEAN RECURRENCE TIME FOR EVENTS WITH MAGNITUDES NOT SMALLER THAN M.

(time in months)

Observation period in months	=	1.1
Mmin	=	.0
Mmax	=	2.5
Mmax observed	=	2.2
Delta M	=	.10
Beta	=	2.06
b-value	=	.90
Total number of events	=	865
N events with M>=Mmin	=	156
Hazard magnitude1	=	3.23
Hazard magnitude3	=	3.23
Sum of moment from haz_mag1	=	.94E+13
Sum of energy from haz_mag1	=	.48E+08

RECCURRENCE TIMES AND EVENTS PER MONTH

M	.50	1.00	1.50	2.00	2.50	3.00
T(M)	.020	.058	.181	.718	*******	*******
T obs	.0201	.0583	.1385	.3693	*******	*******
N(M)	55.0	19.0	6.1	1.5	.0	.0
N obs	55	19	8	3	0	0

t	PROBABILITY OF OCCURRENCE					
1.0	1.0000	1.0000	.9958	.7522	.0000	.0000
2	1.0000	1.0000	1.0000	.9379	.0000	.0000
3	1.0000	1.0000	1.0000	.9842	.0000	.0000
4	1.0000	1.0000	1.0000	.9959	.0000	.0000
5	1.0000	1.0000	1.0000	.9989	.0000	.0000
6	1.0000	1.0000	1.0000	.9997	.0000	.0000
7	1.0000	1.0000	1.0000	.9999	.0000	.0000
8	1.0000	1.0000	1.0000	1.0000	.0000	.0000
9	1.0000	1.0000	1.0000	1.0000	.0000	.0000
10	1.0000	1.0000	1.0000	1.0000	.0000	.0000
11	1.0000	1.0000	1.0000	1.0000	.0000	.0000
12	1.0000	1.0000	1.0000	1.0000	.0000	.0000

Table 5.4. Probability table for Case F - normal seismic catalogue

PROBABILITY OF OCCURRENCE OF A SEISMIC EVENT WITH MAGNITUDE NOT SMALLER THAN M GIVEN TIME t AND T(M) - MEAN RECURRENCE TIME FOR EVENTS WITH MAGNITUDES NOT SMALLER THAN M.

(time in months)

Observation period in months	=	12.0
Mmin	=	2.0
Mmax	=	3.9
Mmax observed	=	3.6
Delta M	=	.10
Beta	=	2.85
b-value	=	1.24
Total number of events	=	11890
N events with M>=Mmin	=	216
Hazard magnitude1	=	4.32
Hazard magnitude3	=	4.31
Sum of moment from haz_mag1	=	.16E+16
Sum of energy from haz_mag1	=	.10E+12

For tau_1998.spr NS 7

RECCURRENCE TIMES AND EVENTS PER MONTH

M	1.00	1.50	2.00	2.50	3.00	3.50
T(M)	.003	.013	.055	.234	1.036	5.858
T obs	.0074	.0177	.0554	.2216	.9205	11.9660
N(M)	3758.7	902.2	216.0	51.2	11.6	2.0
N obs	1627	677	216	54	13	1

t	PROBABILITY OF OCCURRENCE					
1.0	1.0000	1.0000	1.0000	.9858	.6202	.1575
2	1.0000	1.0000	1.0000	.9998	.8551	.2902
3	1.0000	1.0000	1.0000	1.0000	.9445	.4018
4	1.0000	1.0000	1.0000	1.0000	.9786	.4959
5	1.0000	1.0000	1.0000	1.0000	.9917	.5750
6	1.0000	1.0000	1.0000	1.0000	.9968	.6418
7	1.0000	1.0000	1.0000	1.0000	.9988	.6979
8	1.0000	1.0000	1.0000	1.0000	.9995	.7453
9	1.0000	1.0000	1.0000	1.0000	.9998	.7852
10	1.0000	1.0000	1.0000	1.0000	.9999	.8188
11	1.0000	1.0000	1.0000	1.0000	1.0000	.8471
12	1.0000	1.0000	1.0000	1.0000	1.0000	.8710

Table 5.5. Probability table for Case F -events after break in production

PROBABILITY OF OCCURRENCE OF A SEISMIC EVENT WITH MAGNITUDE NOT SMALLER THAN M GIVEN TIME t AND T(M) - MEAN RECURRENCE TIME FOR EVENTS WITH MAGNITUDES NOT SMALLER THAN M.

(time in months)

Observation period in months	=	.6
Mmin	=	1.0
Mmax	=	3.0
Mmax observed	=	2.8
Delta M	=	.10
Beta	=	1.99
b-value	=	.87
Total number of events	=	1026
N events with M>=Mmin	=	57
Hazard magnitude1	=	4.01
Hazard magnitude3	=	4.01
Sum of moment from haz_mag1	=	.38E+14
Sum of energy from haz_mag1	=	.99E+09

RECCURRENCE TIMES AND EVENTS PER MONTH

M	.50	1.00	1.50	2.00	2.50	3.00
T(M)	.004	.010	.028	.083	.298	6.368
T obs	.0043	.0101	.0275	.0721	.2885	*******
N(M)	156.0	57.0	20.4	6.9	1.9	.1
N obs	133	57	21	8	2	0

t	PROBABILITY OF OCCURRENCE					
1.0	1.0000	1.0000	1.0000	1.0000	.9636	.1475
2	1.0000	1.0000	1.0000	1.0000	.9984	.2729
3	1.0000	1.0000	1.0000	1.0000	.9999	.3796
4	1.0000	1.0000	1.0000	1.0000	1.0000	.4704
5	1.0000	1.0000	1.0000	1.0000	1.0000	.5477
6	1.0000	1.0000	1.0000	1.0000	1.0000	.6136
7	1.0000	1.0000	1.0000	1.0000	1.0000	.6697
8	1.0000	1.0000	1.0000	1.0000	1.0000	.7176
9	1.0000	1.0000	1.0000	1.0000	1.0000	.7584
10	1.0000	1.0000	1.0000	1.0000	1.0000	.7933
11	1.0000	1.0000	1.0000	1.0000	1.0000	.8230
12	1.0000	1.0000	1.0000	1.0000	1.0000	.8484

6. Summary and conclusions

The object of the study was to determine whether there is a difference in the seismic response of the rockmass between 11-day mining cycle and full calendar operations - FULCO.

Time-dependent rockmass response is important here since it affects the time of day seismic hazard, which impacts on the exposure of workers to the hazard. The literature survey thus concentrated on the available time displacement data. Few stope closure measurements were found but nothing that could be used in the current research. The criteria required to assess the two mining cycles needed to be developed.

We developed the simplistic concept of Seismic Exposure (SE). We define the hourly hazard as the average number of events greater than magnitude 1. The liability is the average number of workers underground during that hour. The average daily risk (daily SE) is the sum of the hazard and the liability. The full risk for the period under consideration would then be the daily SE multiplied with the number of working days. This can be normalised by production for comparison purposes.

The general seismic hazard is described by conventional seismic hazard statistics. One advantage of a Gutenberg-Richter fit to the data is that the presence or otherwise of one large event need not influence the seismic hazard parameters. This helps to overcome a major problem with seismic hazard back analysis, namely the issue of single very large events that may or may not be included in a seismic event population because of a small change in the spatial or temporal filter parameter.

We introduced here an extension to the Gutenberg-Richter statistics by combining it with Energy-Moment statistics. This idea was first considered under GAP303 and then further developed under the DeepMine 5.1.1 project. Under the latter project a new parameter for quantifying seismic hazard was defined namely the Potential Damage Area (PDA). Combining Gutenberg-Richter statistics, E-M statistics and empirically derived relations between strong ground motion and stress drop, the area is calculated over which strong ground motions could have exceeded a damaging threshold. The advantage of this parameter is that the hazard is expressed in a simple scalar number of m^2 that allows conventional arithmetic calculations, e.g. normalising by production.

The research work involved visiting mines and, with the co-operation of production staff, delineating areas and times where/when mining was done in the conventional 11-day fortnight way and where/when full calendar operations were applied. Further information required was the cage schedules and the number of workers involved in underground production and other work. Lastly the appropriate seismic data was obtained. All the mines used in the study are equipped with ISS's so that the seismic data was largely comparable.

The outcome of the study is summarised in table 6.1. It shows quite variable production figures for the different cases. Since, for the deep, hard rock mines, seismic hazard generally increases with production, normalising the hazard and risk parameters by production is probably fair. Here then we express the risk in terms of daily Seismic Exposure and the general hazard in terms of PDA. The final comparison between 11-day fortnight and full calendar operations is then done by multiplying the daily SE with the number of production days and dividing it by the total centares mined. The Potential Damage Area is expressed as a percentage of the area mined.

Table 6.1 A summary of the results from the four case studies

		11-day Fortnight	FULLCO
Case A	SE/day	201.87	133.23
VCR	N prod. Days	273	349
'scattered longwalls'	PDA	1694	1794
FWR	Centares produced	202712	153129
	SE/centare	0.27	0.30
	PDA/centare x 100	0.84	1.17
Case B	SE/day	48.52	81.40
Main Reef	N prod. Days	234	301
Pillar mining	PDA	828	930
FWR	Centares produced	40105	50503
	SE/centare	0.28	0.49
	PDA/centare x 100	2.06	1.84
Case C	SE/day	115.99	228.08
Vaal Reef	N prod. Days	365	221
Pillar mining	PDA	266	209
Klerksdorp area	Centares produced	75110	85583
	SE/centare	0.56	0.59
	PDA/centare x 100	0.35	0.24
Case D	SE/day	99.50	166.16
Vaal Reef	N prod. Days	388	707
Scattered mining	PDA	444	2874
Klerksdorp area	Centares produced	106574	203671
	SE/centare	0.36	0.58
	PDA/centare x 100	0.42	1.41

Changing from 11-day fortnight operations to FULCO resulted in an increase in the Seismic Exposure per centare in all four cases. The percentage of the production area potentially damaged increased in two of the four cases and decreased in the other two. We thus do not observe a general increase in seismic hazard associated with the increased production achieved through FULCO, but we do find an increase in risk (Seismic Exposure) per centare mined.

The increased production associated with FULCO will have to be achieved by simultaneous adjustment of the fundamental mining methods to contain the seismic risk. In did not happen in the cases studied here.

To test the notion that production days following breaks in production, like Mondays or other days after long weekends, are more hazardous than normal working days and therefore FULCO should be safer, a special analysis on data from two mines was done. The analysis involved the separation of seismic data which occurred on days following breaks, using research software tools developed under GAP303. The seismic hazard represented by the 'after break' subsets of data was then compared to that represented by the full data sets. After normalising for the respective time spans involved, the results showed, in fact, that the seismic hazard is, in fact, lower on days following breaks.

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