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AN EVALUATION OF THE EFFECTIVENESS OF BACKFILL AS REGIONAL SUPPORT IN REDUCING SEISMICITY

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PREFACE

The gold mining industry is currently placing 150 000 tonnes of backfill per month, primarily for the support of mined out excavations. Analyses of falls of ground in conventional and backfilled stopes have shown that backfill provides good local support to the hangingwall so that fewer falls of ground are encountered in backfilled panels compared to conventionally supported panels. However, quantifying the benefits of backfill in terms of regional support has proved more difficult.

This report details the findings of further studies carried out by COMRO staff, on how the filling of large areas with backfill over a significant time period affects seismic energy release compared to that observed in similar unfilled areas.

The results, although inconclusive are encouraging in that they highlight the importance of identifying the sources of seismicity occurring within the area being analysed and quantifying the seismic energy release. Thus, for the first time, an estimate of seismic energy release due to geological structures and to pillar foundation failure is made and compared with the seismic energy released specifically by mining activity. This approach holds considerable promise for an objective evaluation of backfill as regional support and also for the design of more efficient backfill support to replace current regional support systems such as stabilising pillars.

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SUMMARY

This report is concerned with the analysis of seismic data from three sites during mining with and without backfill, in order to determine the effect that backfill has on regional seismicity.

Since the geology and stress fields in any two areas used for comparison cannot be identical, corrections have been made to the data in order to reduce the effect of seismically active geological features.

The seismic data have been evaluated in terms of the number and magnitude of events normalised to area mined, MINSIM-D derived ERR and ESS values, b- values and γ_M values.

Although trends in the data indicate that in certain circumstances backfill causes a reduction in total seismic energy released, it is difficult to obtain firm results from the data. It would seem that data from mines where backfill is being placed on a mine wide basis for extended periods of time can provide conclusive information on the effects of backfill on regional seismicity.

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1 INTRODUCTION

Backfill is an important mining strategy used to reduce rockburst and rockfall hazards on South African mines. Squelch and Gürtunca (1991) carried out research into the effect that backfill has on rockfall accidents and rockburst damage. Using nine case studies covering 601 rockfall accidents and 1,8 million centares of mining, they found that when backfill is placed close to the face with good face area support and 70 per cent backfilling is achieved, significant reductions in rockfall accidents and rockburst damage will occur. It is expected that this reduction would be accompanied by a similar reduction in the magnitude and/or frequency of seismic events. A research programme was therefore set up to determine the influence of backfill on regional seismicity.

Gay *et al* (1988) found that, although a greater number of events occurred in filled areas compared to conventionally supported areas, the events were smaller in magnitude and seismic energy was released at a more uniform rate than in unfilled stopes. In unfilled stopes the rate of seismic energy release was irregular with periods of relatively little seismicity punctuated by larger events. They noted that geology could have influenced these results.

Hemp and Goldbach (1991) investigated the seismicity recorded at four sites during mining with and without backfill. They found that in two of the four cases a greater number of events occurred in filled panels than in unfilled panels. However, this increase was only in the small magnitude ranges. In both cases over 100 000 m^2 had been mined during the period of interest.

In the remaining two cases it was found that both the number of events and the released seismic energy increased in filled panels compared to unfilled panels. However, in both cases there were seismically active geological features in the areas of interest. It is believed that those features largely controlled the seismicity in those areas, irrespective of the presence or absence of backfill. In both these cases less than 50 000 m^2 had been mined during the period of interest.

This report continues this research by analysing seismic data from three sites during mining with and without backfill.

2 SITE INFORMATION AND DATA SELECTION

2.1 Western Deep Levels 110-114 Level

The first set of data was recorded by the Western Deep Levels regional seismic network. The data cover two adjacent longwalls on East mine. In this area the Carbon Leader reef dips at 22° south and the up dip panel is being mined at a depth of approximately 3 300 m. The up dip panels of 110 level are intersected by the Wuddles dyke which has an associated throw of 2 m. All panels on 113 level are intersected by the Chisa fault (see Figure 1).

The two longwalls, 110-112 and 113-114 levels, were mined without backfill until the beginning of 1989. Since then classified tailings have been used on both longwalls. The backfill is placed on average 7 m back from the face and between 65 and 75 per cent backfilling has been achieved. The rate of mining in both panels is approximately equal with between 8 and 11 m face advance per month.

The data were recorded using a mine-wide seismic system which detects and locates more than 600 events in the magnitude range -0,5 to 5,0 per month. Data were obtained for the period December 1986 to September 1991.

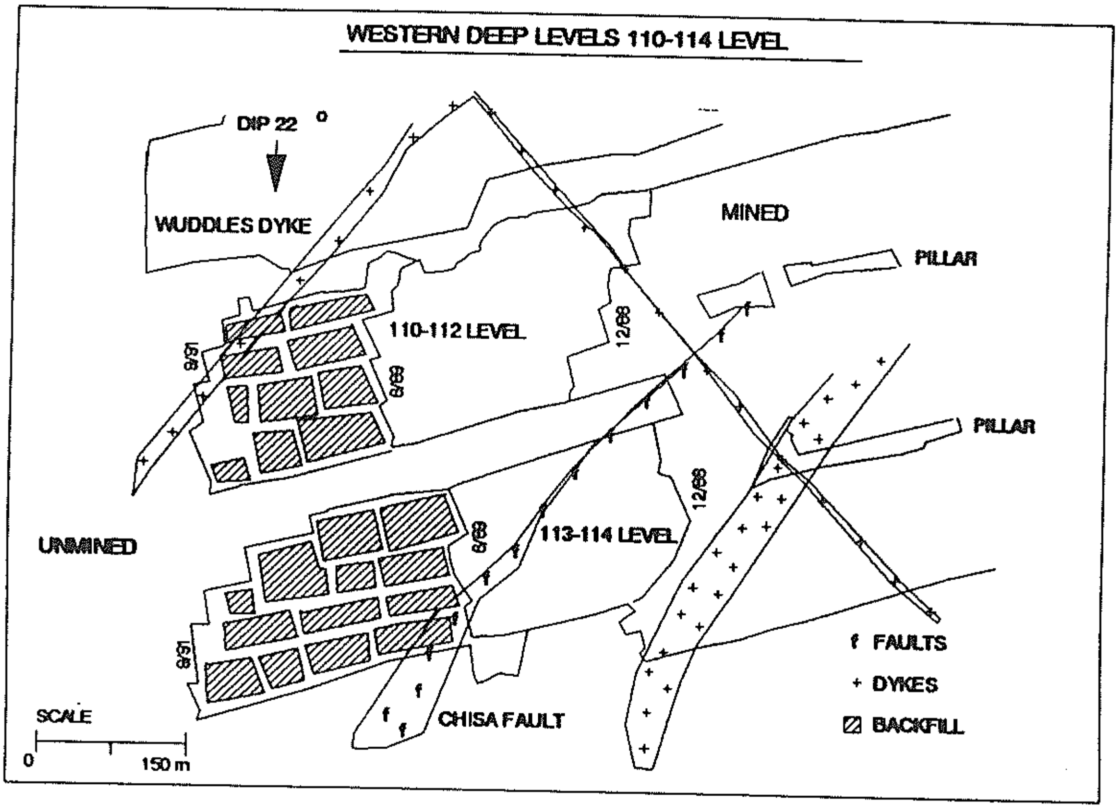

Figure 1 PLAN OF WDL 110-114 LEVEL SHOWING GEOLOGY AND MINING LAYOUT

Data selection

For meaningful results, the data selected for analysis should be from two areas with virtually identical geological features. Since it is very difficult to obtain such data sets, it was decided that the effects of geological features should be minimised as far as possible by careful data set selection.

In order to determine the effect that the geological features in this area have on the seismicity, contours of the seismic event density were plotted. These contours, superimposed on the geology, are shown in Figure 2.

From this figure it is obvious that the geology does influence the seismicity. The three largest peaks on 110-112 level are located on geological features. The correlation between peaks and geological features on 113-114 level is not as strong but is still evident with contours running parallel to the geological structures. In order to correct for the effect of the geological features, the events occurring on these geological features were excluded from the data set. This type of data selection is still not ideal since events occurring 50 m up in the hangingwall, on a dyke dipping at 70°, will be located approximately 20 m away from the feature in plan. A 40 m band around each feature would greatly reduce the size of the data set and probably exclude a number of events which are not directly related to the feature. Likewise, a number of events which occurred as a result of the geological features may be located sufficiently far away from the feature for them to be included in the data set. Since it is the larger events which have the greatest influence on the values of seismic parameters, these problems have been reduced by making careful checks on the locations of the larger events.

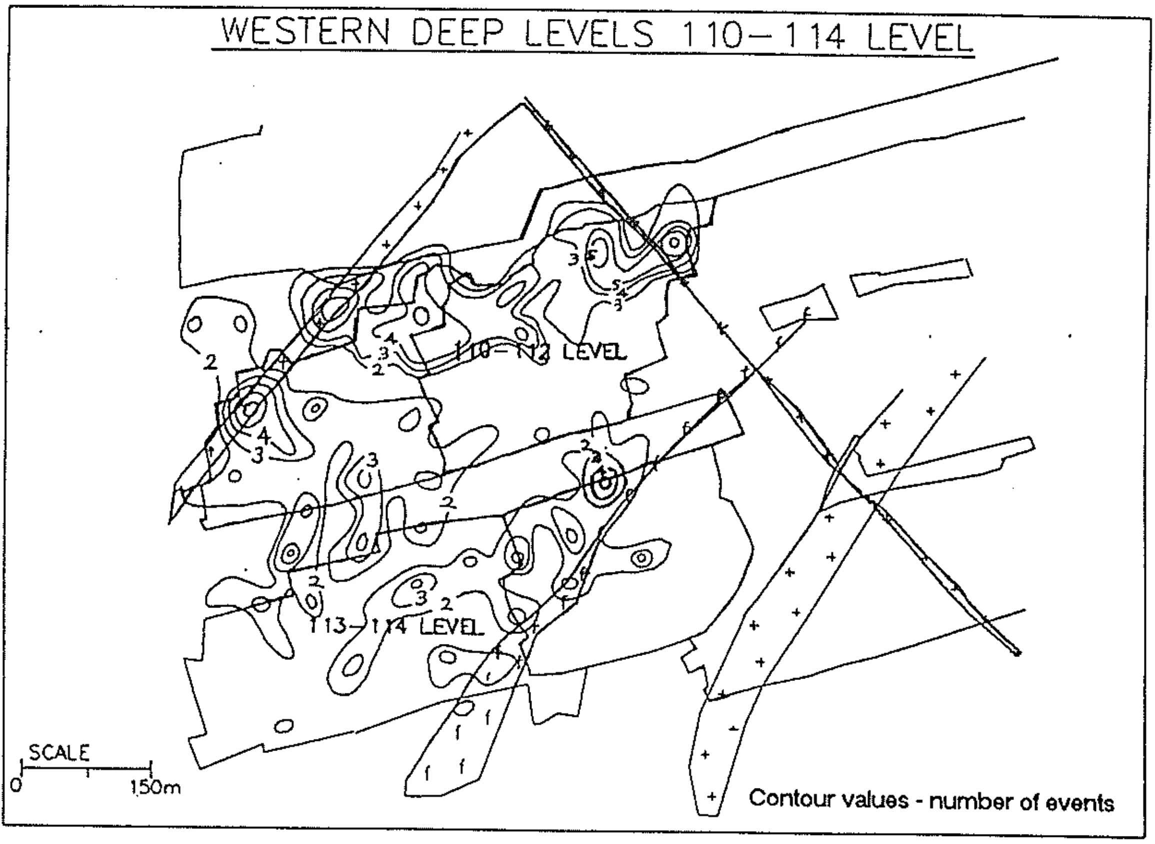

Figure 2 WDL 110-114 LEVEL SEISMIC EVENT DENSITY CONTOURS

The data set consists of two time periods during which mining took place without fill and two time periods during which mining took place with fill.

2.2 Western Deep Levels 83-90 Level

Seismic data from two longwalls on Western Deep Levels East mine were considered by Hemp and Goldbach, 1990. In that study, data recorded up until December 1989 were analysed. This report re-evaluates data from the same site using the most recent data, ie from November 1987 to December 1991. Data from a third longwall - 83 Level are also considered in this report.

These data were recorded by the Western Deep Levels regional seismic network. In this area the Carbon Leader reef dips at 24° to the south and the up dip panel is being mined at a depth of approximately 2200 m. The area is cut by a number of dykes and faults which have associated seismicity (see Figure 3).

88-90 Level East was mined without backfill until the beginning of 1991. 85-87 Level and 83 Level have been mined with classified tailings backfill since 1987. Hydraulic props are placed at the face and timber packs are used in the gullies. The backfill is placed on average 7 m back from the face and between 60 and 70 per cent backfilling has been achieved. The face advance is between 10 and 12 m per month. In order to exclude the period of mining with fill on 88-90 level, data used in this analysis only cover the period from December 1987 to May 1991.

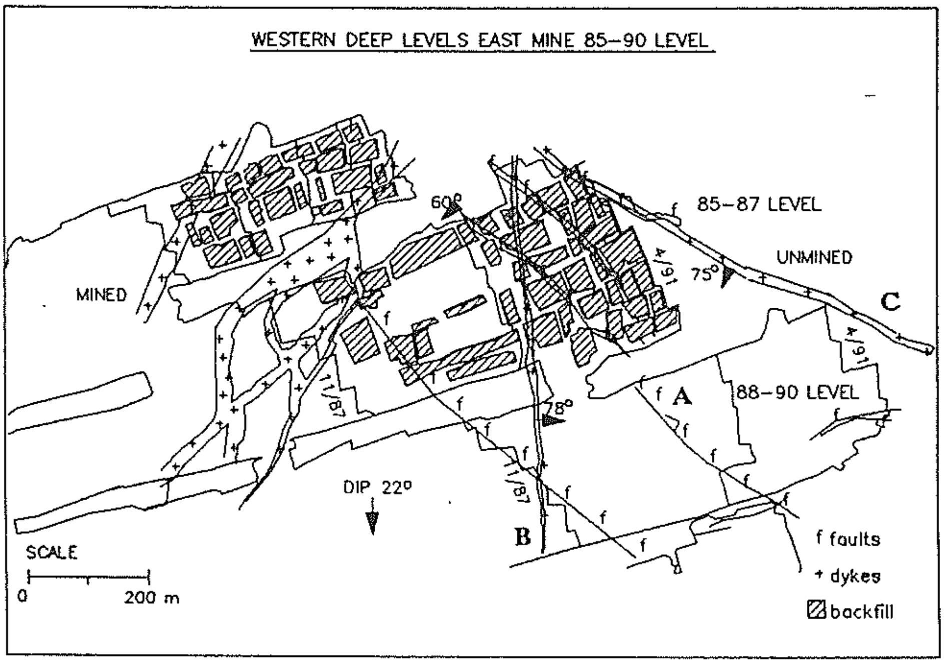

Figure 3 PLAN OF WDL 83-90 LEVEL SHOWING GEOLOGY AND MINING LAYOUT

Data selection

This area is intersected by a number of geological features. In order to determine the effect that these features have on the seismicity, seismic event density contours were plotted. These contours superimposed on the geology are shown in Figure 4.

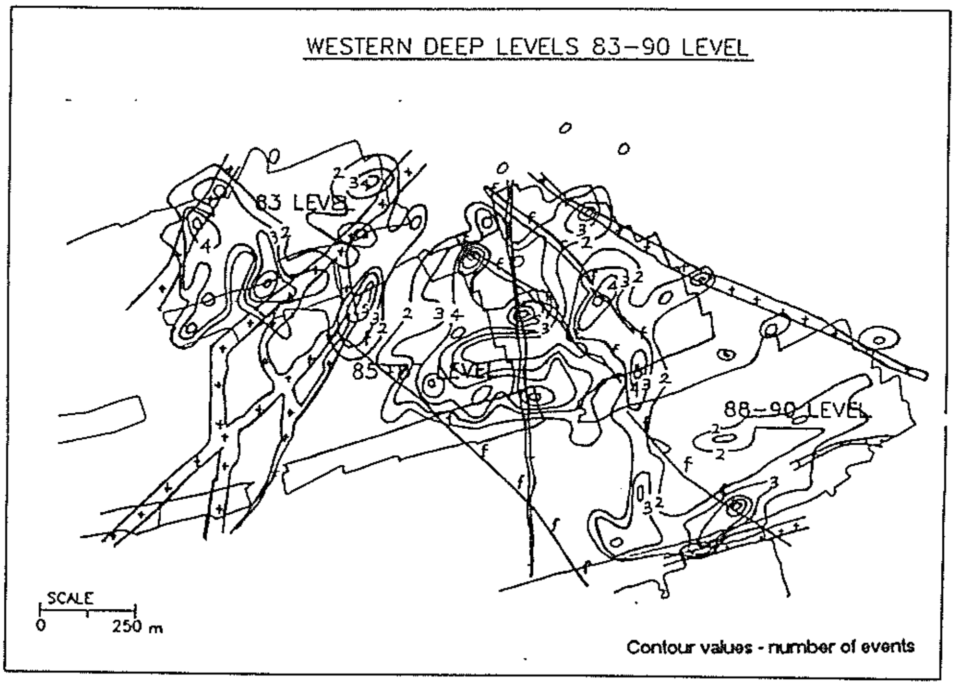

Figure 4 WDL 83-90 LEVEL SEISMIC EVENT DENSITY CONTOURS

From this figure it is evident that there is a remarkable correlation between seismicity and geological structures. For this reason events located on or very close to geological features were excluded from the data set.

2.3 Vaal Reefs 2K

Data from this site were also analysed by Hemp and Goldbach, 1990. In that study, data covering the period January 1978 to December 1989 were used. This report updates those results by considering the most recent seismic data from that area, ie until February 1992.

These data were recorded by the Klerksdorp regional seismic network and cover the 2K area of Vaal Reefs gold mine. The area under consideration is intersected by numerous faults and dykes which have associated seismicity. The reef lies at approximately 2 600 m below surface (see Figure 5).

Scattered mining without backfill took place in this area from 1978 until January 1984 after which classified tailings backfill was introduced. The backfill is placed between 4 and 8 m from the face and 70 per cent backfilling has been achieved.

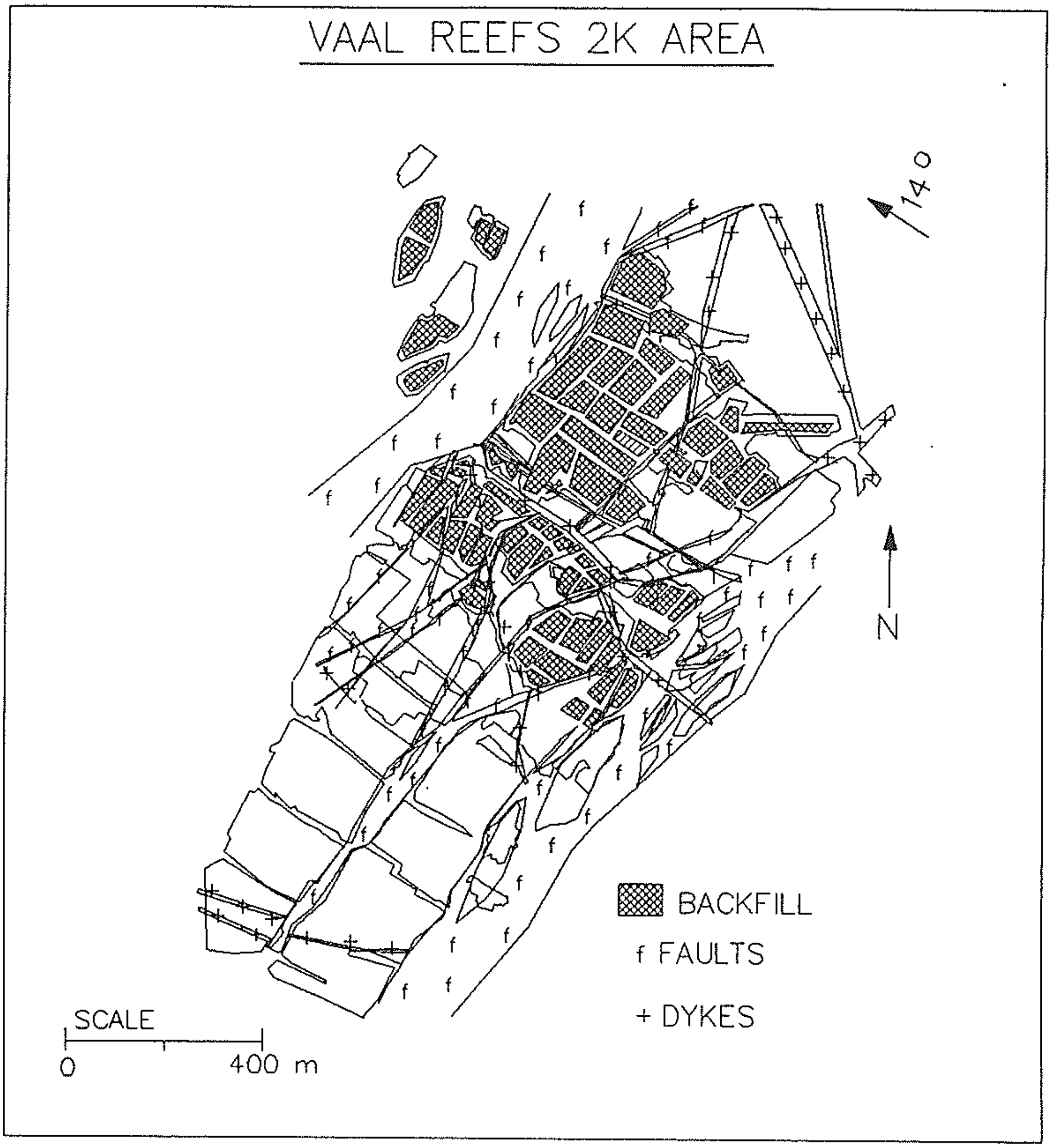

Figure 5 PLAN OF VAAL REEFS 2K AREA SHOWING MINING LAYOUT AND GEOLOGY

Data selection

Because of the complicated nature of the geology in this area, no attempt has been made to distinguish between events that occur as a result of geological structures and those that do not. The geological structure of the area covered during mining without backfill (7/78 - 6/84) is less complicated than that in the area covered during mining with backfill (7/84 - 1/92).

3 RESULTS

Similar analyses have been performed on all data sets, with the exception that there has been no numerical modelling of the scattered mining in the Vaal Reefs area.

Since the amount of mining in any two areas being used for comparison is not necessarily equal, all seismic parameters have been normalised with respect to 1000 m^2 mined.

3.1 Western Deep Levels 110-114 Level

Figure 6 shows the seismic events which make up these data sets.

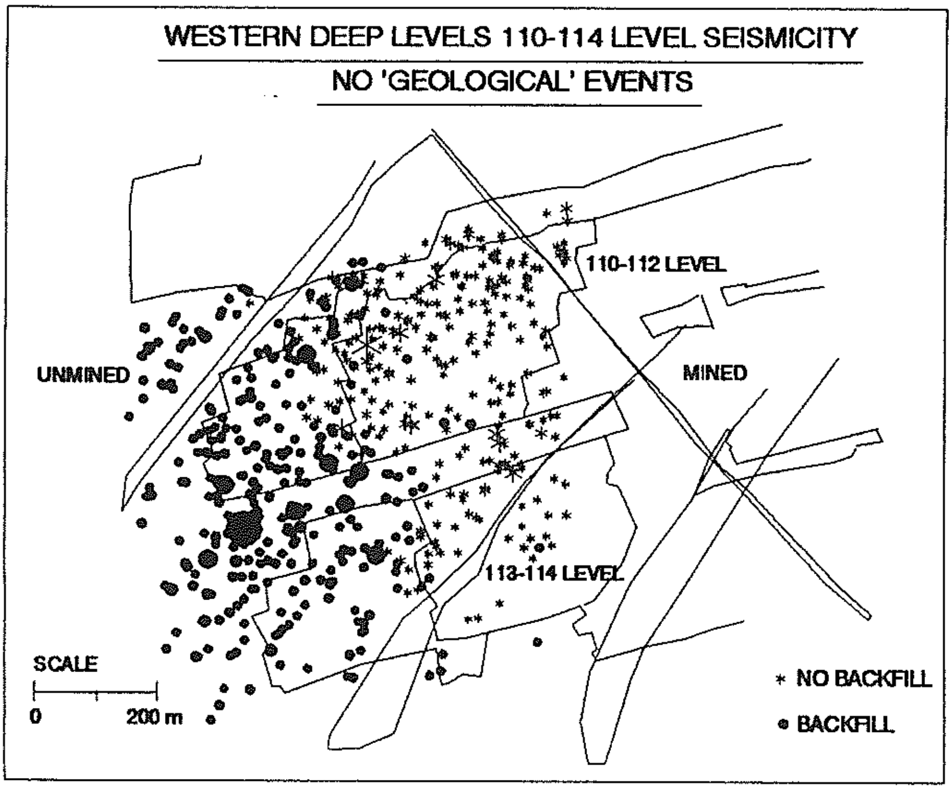

Figure 6 WDL 110-114 LEVEL SEISMIC EVENTS

3.1.1 Level 110-112

Table 1 contains a summary of the seismic data from this area. The time periods and areas mined during mining with and without fill are comparable.

TABLE 1. WESTERN DEEP LEVELS 110-112 LEVEL

	NO BACKFILL	BACKFILL
TIME PERIOD	1.12.86-30.6.89	1.7.89-30.9.91
AREA MINED (m^2)	30720	24730
TOTAL EVENTS > 0,0	207	135
EVENTS 1 < M_L < 2	46	32
EVENTS 2 < M_L < 3	15	6
EVENTS M_L > 3	2	1
EVENTS/1000 m^2	6,74	5,46
EVENTS > 1/1000 m^2	1,50	1,29
EVENTS > 2/1000 m^2	0,49	0,24
EVENTS > 3/1000 m^2	0,065	0,04
MAX MAG	3,1	3,0
ENERGY (MJ)	9433	4440
ENERGY/1000 m^2 (MJ/m^2)	307,2	179,5
b VALUE	0,54	0,61
ERROR IN b	0,08	0,11
γM	0,21	0,12

From these results it is evident that a smaller number of events occurred during mining with fill than during mining without fill. There is a reduction in the number of events occurring per 1000 m^2 in all magnitude ranges.

Approximately half as much seismic energy was released during mining with fill as during mining without fill.

The b-values do not differ significantly and they indicate that in this area backfill does not cause any real change in the ratio of small to large events. (See Appendix A for explanation of b and γ_M values.)

The value γ_M is a direct measure of the seismic deformation associated with mining activity. These values indicate that seismically induced deformation varies from 21 per cent during mining without fill to 12 per cent during mining with fill. This smaller value indicates that the introduction of backfill has reduced the likelihood of the rock to deform seismically.

From Figure 6 it is evident that a number of large events located on or very close to the stabilising pillars in this area. For this reason data was also analysed in terms of the number and magnitude of these 'pillar' events. Table 2 contains a summary of the number of events occurring on the pillars as well as the percentage contribution that these events make to the total seismicity in the area.

TABLE 2. WESTERN DEEP LEVELS 110-112 LEVEL - PILLAR FAILURE DATA

	NO BACKFILL		BACKFILL	
TOTAL EVENTS > 0,0	50	(24,2 %)	47	(34,8 %)
EVENTS 1 < M_L < 2	13	(28,3 %)	7	(21,9 %)
EVENTS 2 < M_L < 3	7	(46,7 %)	5	(83,3 %)
EVENTS M_L > 3		-	1	(100 %)
MAX MAG	2,8		3,0	
ENERGY (MJ)	1912	(20,3 %)	3862	(87,0%)

From these results it is evident that there is considerable pillar failure in this area. The seismicity associated with this failure contributes significantly to the total seismicity in the area. As the length of the pillar increases this effect becomes more pronounced. These results indicate that backfill does not seem to affect pillar failure at this depth.

Figure 7 shows the cumulative number of events as a function of time for each time period. A flattening off in the number of events is evident during the period of backfilling while the curve for the unfilled period shows a steady increase.

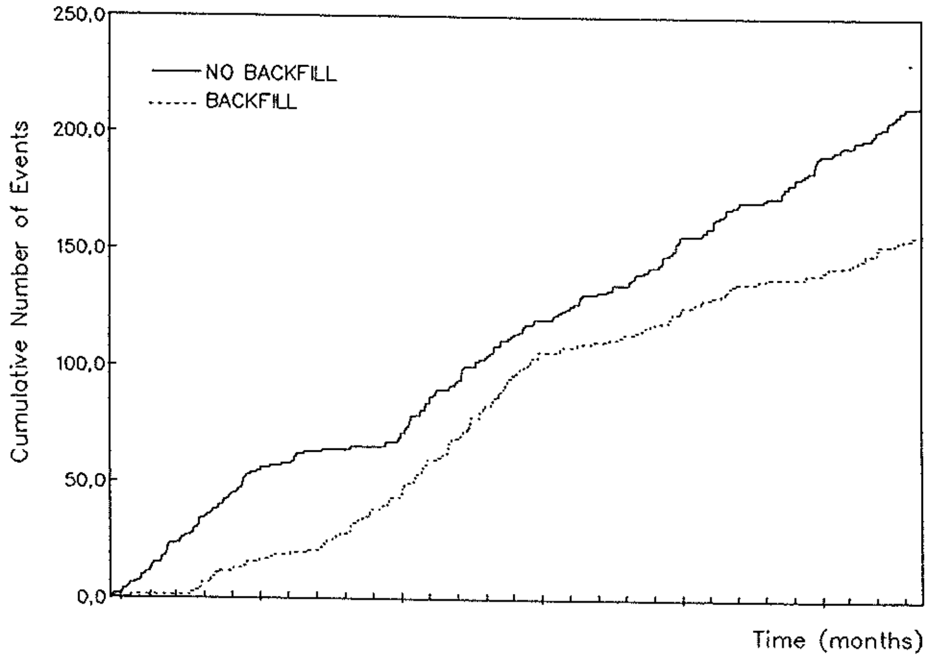

Figure 7 WDL 110-112 LEVEL CUMULATIVE NUMBER OF EVENTS

The decrease in the number of events recorded during mining with fill is evident in Figure 8 where the cumulative seismic moment is plotted as a function of time. The curve is made up of a larger number of smaller steps in the filled case than in the unfilled case - where a small number of large events control the shape of the curve.

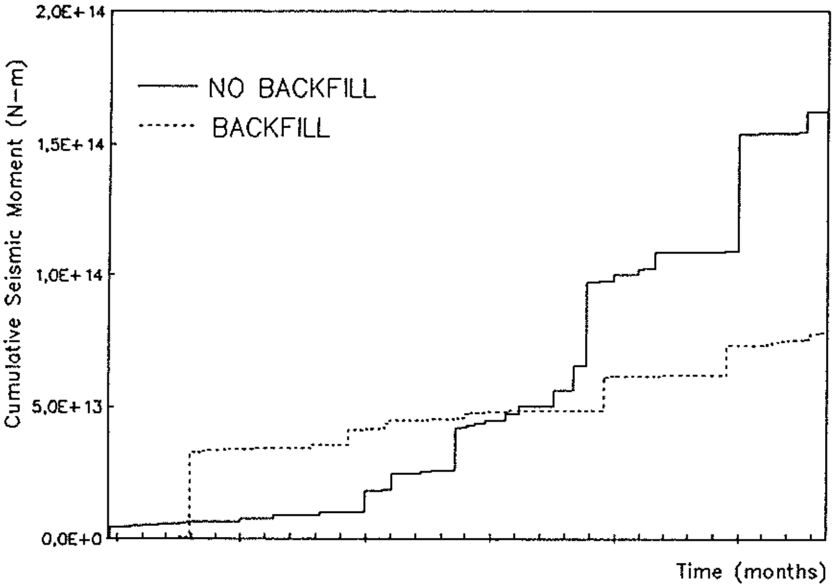

Figure 8 WDL 110-112 LEVEL CUMULATIVE SEISMIC MOMENT

MINSIM-D runs were carried out for three different face positions. Table 3 lists the energy release rate values obtained for each of these face positions.

TABLE 3. ERR VALUES FOR WDL 110-112 LEVEL FROM MINSIM-D RUNS

FACE POSITION	ERR VALUE (MJ/m2)
Dec 86	24,6
July 89	16,1
Sep 91	16,6

The presence of stabilising pillars and the introduction of backfill cause a reduction in the ERR values calculated by MINSIM-D. In this particular area the reduction in the ERR value after the introduction of fill is accompanied by a reduction in the seismicity level.

The magnitude of an impending seismic event that would result from slip over a given area of positive excess shear stress (ESS) can be estimated using the following equation, Ryder (1986).

$M = (\log 2\tau_e \, a^2 l / 1{,}5) - 6{,}07$ where τ_e is peak ESS

a is the half width of positive lobe

l is the strike length of the lobe

ESS values have been calculated for a number of planes co-incident with the geological features in each data set. Webber (1989) found that, using a k-ratio of 0,4, a good correlation existed between the theoretical ESS derived magnitudes and the actual measured magnitude. This type of analysis can be used to determine whether backfill has any effect on the magnitude of an event that results from slip over a given region.

Using the above equation and the following values from a MINSIM-D run with an ESS sheet at the face :- τ_e = 37,5 MPa, a= 60 m and l=180 m, with a k-ratio of 0,4 (Webber, 1989), a theoretical magnitude of 3,1 is calculated. It should be noted that this is a rough estimate given the irregular shape of the ESS lobe. This value correlates well with the magnitude 3,2 event which did occur on this dyke. This would indicate that backfill may not affect the magnitude of a seismic event that occurs as a result of slip on a dyke.

3.1.2 Level 113-114

Table 4 contains a summary of the seismic data from this area.

TABLE 4. WESTERN DEEP LEVELS 113-114 LEVEL

	NO BACKFILL	BACKFILL
TIME PERIOD	1.12.86-30.6.89	1.7.89-30.9.91
AREA MINED (m^2)	26832	35151
TOTAL EVENTS > 0,0	62	109
EVENTS 1 < M_L < 2	19	26
EVENTS 2 < M_L < 3	5	7
EVENTS/1000 m^2	2,31	3,10
EVENTS > 1/1000 m^2	0,71	0,74
EVENTS > 2/1000 m^2	0,19	0,20
MAX MAG	2,60	2,90
ENERGY (MJ)	1660,2	3886
ENERGY/1000 m^2 (MJ/m^2)	61,9	110,5
b VALUE	0,52	0,54
ERROR IN b	0,14	0,11
γM	0,04	0,07

The periods covering mining with backfill and without backfill are approximately equal. For the same periods of time approximately 35 per cent more mining has taken place during mining with fill than without fill.

There is an increase in almost all seismic parameters listed in this table during mining with fill compared to mining without fill. The increase in the number of events is consistent for all magnitude ranges. The largest magnitudes recorded in each area and the energy/1000 m^2 mined values are larger with backfill. Considering the magnitude of the errors in the b-values the difference between the two values is not significant.

Once again an analysis of the events located or close to stabilising pillars has been carried out. Table 5 contains a summary of the 'pillar' data.

The seismicity associated with pillar failure contributes significantly to the total seismicity in the area. Once again there is an increase in the total energy released at the pillar with increasing pillar maturity. The placement of backfill has not stabilised the pillar.

TABLE 5. WESTERN DEEP LEVELS 113-114 PILLAR FAILURE DATA

	NO BACKFILL		BACKFILL	
TOTAL EVENTS > 0,0	23	(37,1 %)	36	(33,0 %)
EVENTS 1 < M_L < 2	6	(31,6 %)	3	(11,5 %)
EVENTS 2 < M_L < 3	4	(80,0 %)	5	(71,4 %)
MAX MAG	2,6		2,9	
ENERGY (MJ)	1365	(82,0 %)	3064	(78,8 %)

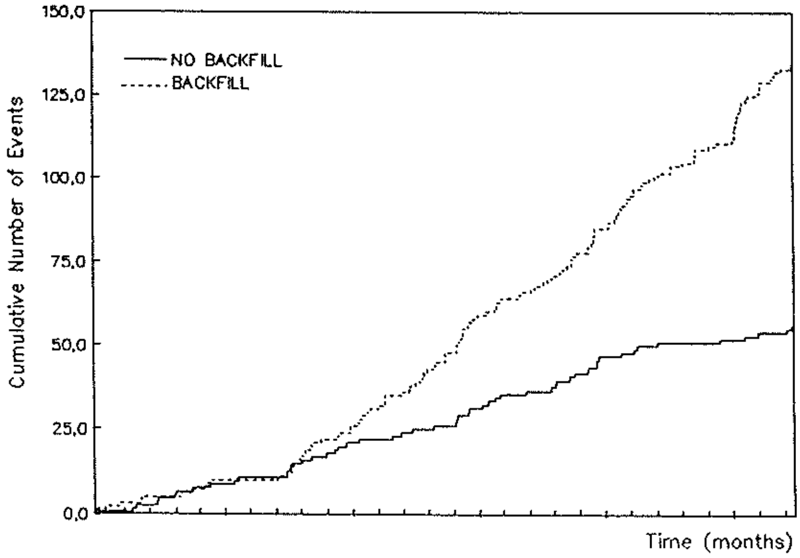

Figure 9 WDL 113-114 LEVEL CUMULATIVE NUMBER OF EVENTS

Figures 9 and 10 show the cumulative number of events and moments as a function of time for each time period. Both curves show reverse trends to those recorded for 110 level.

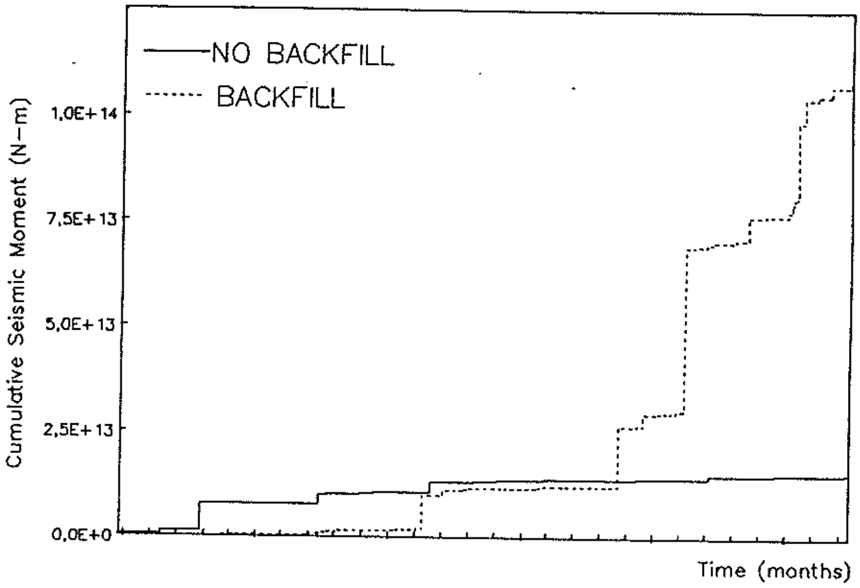

Figure 10 WDL 113-114 LEVEL CUMULATIVE SEISMIC MOMENT

It should be noted that there are several events that occurred during the period of mining with backfill that are larger than the largest event that occurred during the period of mining without fill.

These results are most probably a result of the fact that the seismicity recorded during mining without fill was unusually low for faces at this depth. A comparison between values obtained during mining without fill on this longwall and values obtained for 110-112 level shows that parameters from 113 level are approximately 30 per cent of those recorded on 110 level. The parameters recorded during mining with fill for 113 level are all considerably lower than those recorded during mining without fill on 110 level. The low γ_M value prior to the introduction of fill indicates that less than 4 per cent of mining induced deformation leads to seismicity.

MINSIM-D runs were carried out for three different face positions. Table 6 lists the energy release rate values obtained for each of these face positions.

TABLE 6. ERR VALUES FROM MINSIM-D FOR WDL 113-114 LEVEL

FACE POSITION	ERR VALUE (MJ/m^2)
Dec 86	23,1
Jul 89	16,1
Sep 91	17,1

Once again a drop of approximately 30 per cent in ERR values is evident after the introduction of backfill and stabilising pillars. These lower ERR values do not correlate with the increased seismicity levels during mining with backfill. Therefore changes in ERR values should not be used to determine changes in seismicity levels.

ESS values were calculated for a plane running parallel to the Chisa fault which cuts through this level. Because of the oblique angle of this fault, a number of MINSIM-D runs were carried out covering a number of different face positions. However, none of the runs produced positive ESS lobes in this panel that were at all substantial.

3.2 Western Deep Levels 83-90 Level

Hemp and Goldbach (1990) analysed data from 85 - 90 Level and found that there was an increase in seismic energy released during mining with backfill in this area, compared to mining without fill. They also noted that the seismic data were strongly influenced by geological features.

This data set covers two areas in which mining was taking place with backfill and one area in which no backfill was being placed. Figure 11 shows the seismic events which make up this data set and Table 7 contains a summary of the seismic data from this area.

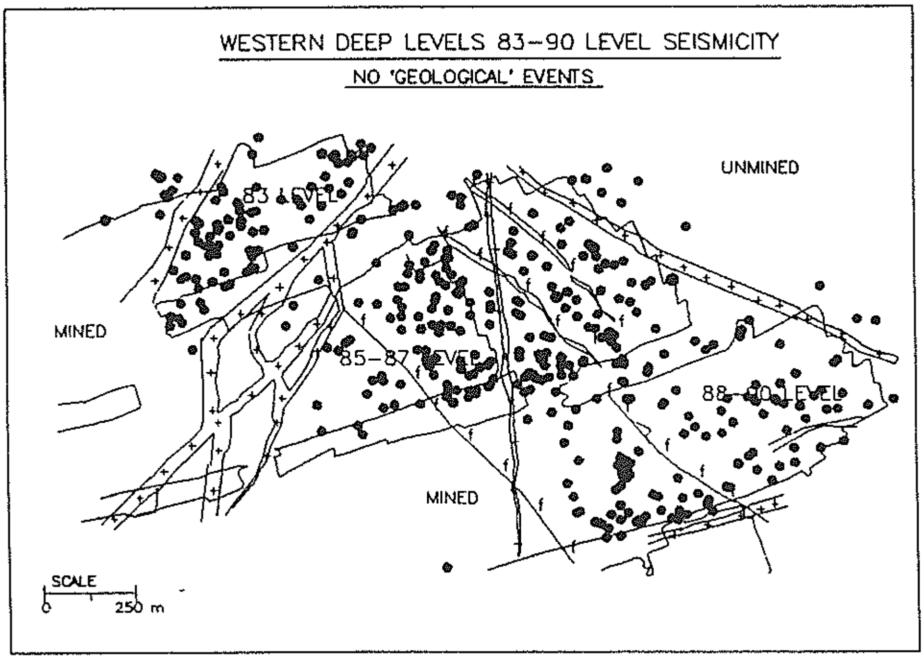

Figure 11 PLAN OF WDL 83-90 SEISMICITY

There is an increase in the number of events recorded in both backfilled areas compared to the unfilled area. This increase is evident for all magnitudes except that of events with magnitude greater than 3,0. The maximum magnitude event recorded during mining without fill is larger than those during mining with fill in both areas. However, the normalised energy released values are larger in the filled cases. This is a result of the large number of events with magnitudes between two and three.

TABLE 7. WESTERN DEEP LEVELS 83-90 LEVEL

	NO BACKFILL	BACKFILL 83 LEVEL	BACKFILL 86 LEVEL
TIME PERIOD	1.11.87-30.4.91	1.11.87-30.4.91	1.11.87-30.4.91
AREA MINED (m^2)	87000	29870	80747
TOTAL EVENTS > 0,0	129	90	172
EVENTS $1 < M_L < 2$	25	23	42
EVENTS $2 < M_L < 3$	2	5	7
EVENTS $M_L > 3$	1	-	-
EVENTS/1000 m^2	1,48	3,01	2.13
EVENTS > 1/1000 m^2	0,29	0,77	0.52
EVENTS > 2/1000 m^2	0,023	0,17	0.087
EVENTS > 3/1000 m^2	0,011	-	-
MAX MAG	3,1	2,6	2.8
ENERGY (MJ)	3357	1390	4133
ENERGY/1000 m^2 (MJ/m^2)	38,6	46,5	51.18
b VALUE	0,72	0,60	0.59
ERROR IN b	0,14	0,14	0.10
γM	0,026	0,031	0.034

The b-values calculated for the two backfilled areas are virtually the same while these two values do differ slightly from the value calculated for the area where mining is taking place without fill. The smaller values for the backfill data indicate a decrease in the ratio of small to medium events, ie a greater number of medium/large events are occurring, contrary to the findings of Gay *et al.*

The γ_M values listed in the table are not significantly different although they are all considerably smaller than the values obtained for other data sets. These small values indicate a low likelihood of the rock to deform seismically as a result of mining activity.

Once again events that located on or close to the stabilising pillars in this area were analysed. The results from this analysis indicated that pillar failure contributed about 2 per cent of the total seismic energy released in this area. The extent of pillar failure at this depth is therefore considerably less than that at 3 500 metres. There should therefore be a re-evaluation of appropriate pillar dimensions for mining at a depth of 3 500 metres.

A plot of the smoothed maximum magnitudes recorded each month is shown in Figure 12. It can be seen that in general the values recorded in the backfilled panels are higher than those recorded in the unfilled panels. The difference between the two becomes less significant near the end of the period under consideration. The maximum magnitudes recorded on 83 level are generally smaller than those recorded in the other filled panel (85-87 level), and after July 1989 they are generally smaller than those recorded in the unfilled panel.

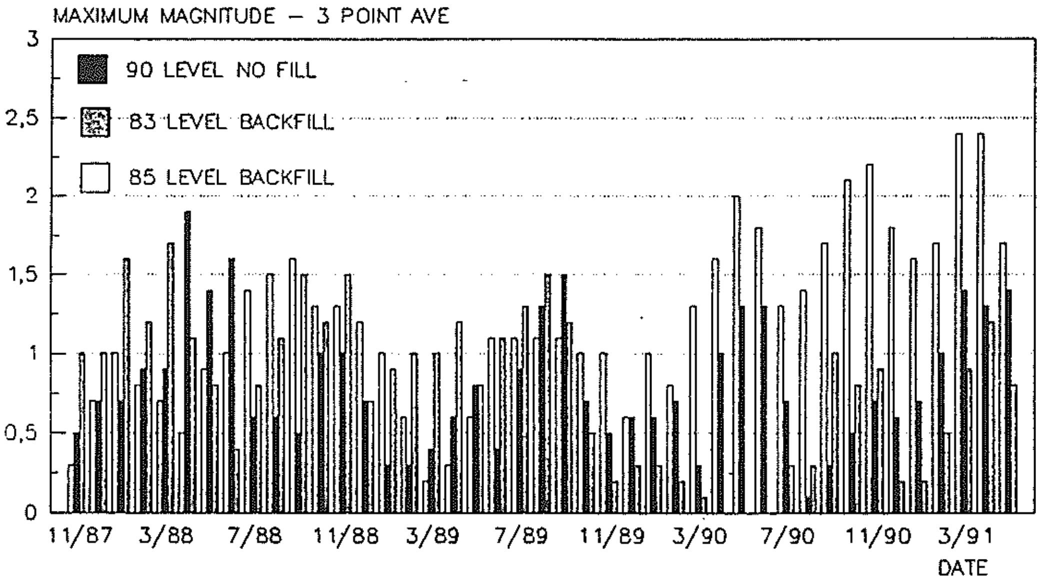

Figure 12 WDL 83-90 LEVEL SMOOTHED MAXIMUM MAGNITUDES

Because of the large difference between the amount of mining that took place on 83 level and the other two longwalls during the period of interest, a comparison of the cumulative moments and cumulative number of events is restricted to the data from 85- 90 level.

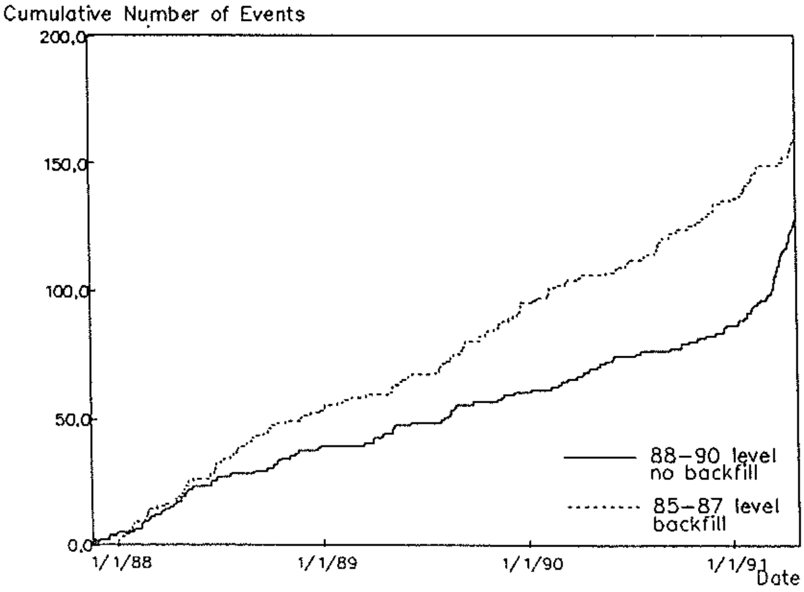

Figure 13 WDL 85-90 LEVEL CUMULATIVE NUMBER OF EVENTS

The cumulative number of events as a function of time is given in Figure 13. This graph shows a flattening off of the number of events at the filled site and then a rapid increase near the end of the graph which considerably reduces the difference between the two curves.

The cumulative seismic moments recorded in both areas are shown in Figure 14. From these graphs it is evident that the total seismic moment in the unfilled panel is dominated by one large event of magnitude 3,1. The seismic moment in the backfilled panel is controlled by two or three large events. Neither data set shows a constant increase in values over time.

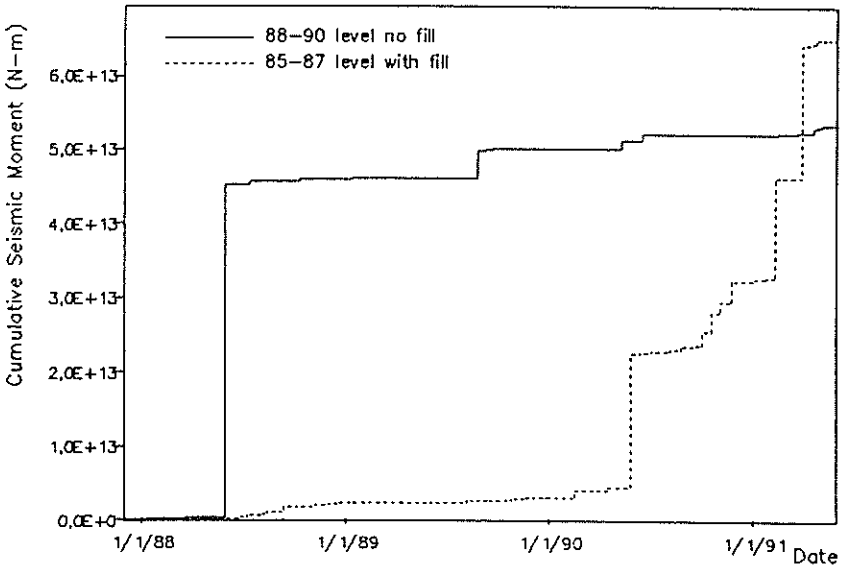

Figure 14 WDL 85-90 LEVEL CUMULATIVE SEISMIC MOMENT

MINSIM-D runs were carried out for three different face positions. Table 8 lists the energy release rate (ERR) values obtained for each of these face positions.

TABLE 8. ERR VALUES FOR 85-90 level

	ERR VALUE (MJ/m^2)	
FACE POSITION	NO BACKFILL	BACKFILL (86 LEVEL)
Before fill	12,8	17,0
Dec 88	14,0	15,3
Jan 92	14,0	14,7

The ERR values prior to the introduction of backfill are considerably smaller in the unfilled panels than in the filled panels. After 18 months of filling the difference between the two had been reduced, and at the current face position the difference between the two is no longer significant. Once again there is no correlation between the ERR values and the seismicity levels.

These results are all consistent with previous results obtained from this area.

Excess Shear Stresses were calculated on a number of planes co-incident with geological features. Sheet A was co-incident with the fault cutting through both longwalls, marked **A** in Figure 3. This fault dips at an angle of 60° SW. Sheet B was co-incident with the dyke running S through both panels (marked **B** in Figure 3). The dyke dips at 78° to the East. Sheet C was co-incident with the dyke cutting through the top panel of 85 level (marked **C** in Figure 3). This dyke dips 75° SW.

Table 9 lists the parameters used for calculating theoretical maximum magnitudes for each of the sheets as well as the maximum recorded event associated with each feature.

TABLE 9. PARAMETERS USED FOR CALCULATING THEORETICAL MAGNITUDES

SHEET	τe	a	l	MAGNITUDE	MEASURED MAGN.
A (FAULT)	37,5 MPa	70	240	3,2	3,3
B (DYKE)	45 MPa	70	200	3,2	3,1
C (DYKE)	27,5 MPa	40	170	2,7	3,1

It should be noted that these are rough estimates given the irregular shape of the ESS lobes. The values obtained for these sheets tie in well with the fact that ESS modelling is known to underestimate the magnitude of an impending event (Webber, 1989). These results also validate the data selection technique whereby events occurring on geological features were excluded from the data set.

3.3 Vaal Reefs 2K

Hemp and Goldbach (1990) found that data from this area showed an increase in the number of events recorded during backfilling, but this increase was restricted to events in the lower magnitude ranges. They also noted an increase in the b-value and a decrease in the γ_M value after the introduction of fill.

Figure 15 shows the seismic events which make up this data set.

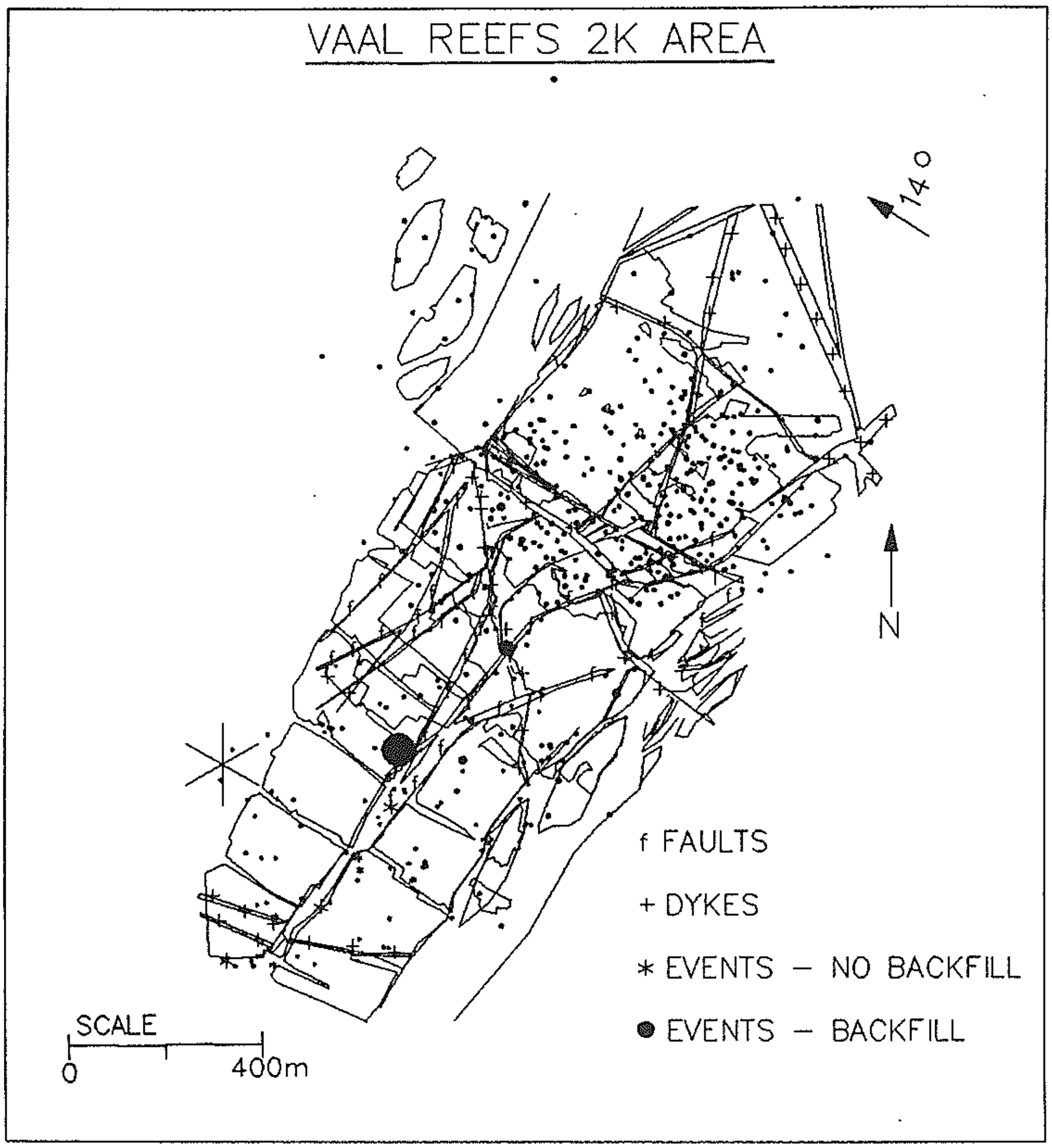

Figure 15 VAAL REEFS 2K AREA SEISMIC EVENTS

Table 10 contains a summary of the seismic data for this area.

There is an increase in the total number of events recorded during the period when mining was taking place with backfill. This increase is in part a result of changes made to the seismic network recording the data, which increased the sensitivity of the network thus affecting the number of smaller events recorded.

Values for the released seismic energy confirm these findings, since both the total and normalised values are larger for the period of mining without backfill. Figures 16 and 17 show the cumulative seismic moment for each time period.

TABLE 10. VAAL REEFS 2K

	NO BACKFILL	BACKFILL
TIME PERIOD	7.78- 6.84	7.84-2.92
AREA MINED (m^2)	262610	556460
TOTAL EVENTS > 0,0	116	692
EVENTS 1 < M_L < 2	54	309
EVENTS 2 < M_L < 3	20	109
EVENTS M_L > 3	11	8
EVENTS/1000 m^2	0,44	1,24
EVENTS > 1/1000 m^2	0,20	0,55
EVENTS > 2/1000 m^2	0,08	0,20
EVENTS > 3/1000 m^2	0,03	0,01
MAX MAG	4,9	4,3
ENERGY (MJ)	9,19x10^5	2,46x10^5
ENERGY/1000 m^2 (MJ/m^2)	3500	442
b VALUE	0,50	0,70
ERROR IN b	0,10	0,09
γM	2,33	0,29

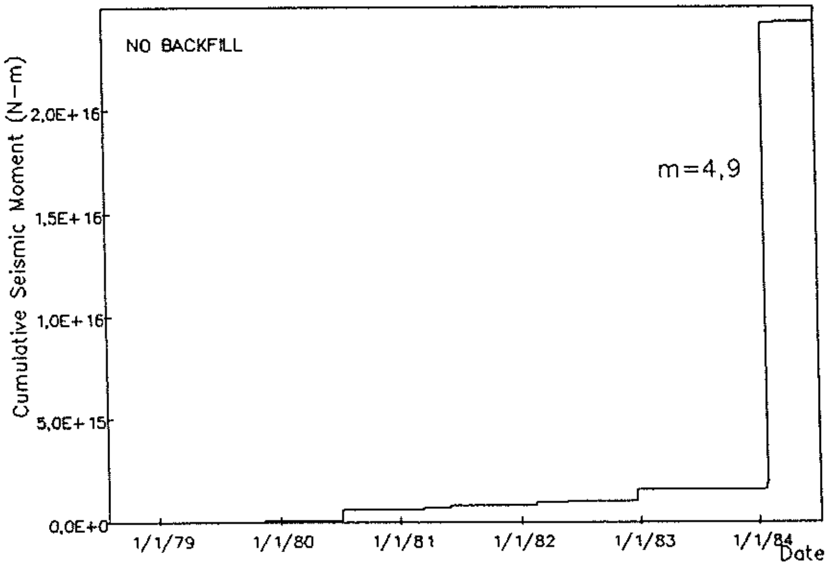

Figure 16 VAAL REEFS 2K AREA CUMULATIVE SEISMIC MOMENT - NO BACKFILL

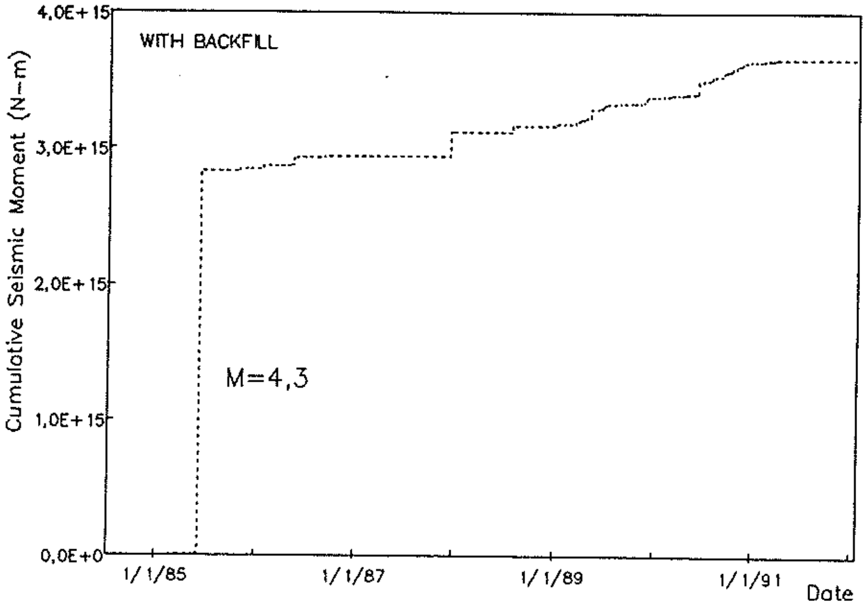

Figure 17 VAAL REEFS 2K AREA CUMULATIVE SEISMIC MOMENT - WITH BACKFILL

The cumulative moment values for the period during mining with backfill show a flattening off after about a year of backfilling. The large step is a result of a magnitude 4,3 event which occurred in May 1985. The location of this event can be seen on Figure 15 (solid circle). After this event the energy is released in a large number of smaller events and a small number of larger events. The cumulative moment for the period of mining without backfill is dominated by a magnitude 4,9 event which occurred in January 1984 (see Figure 15 - asterisk).

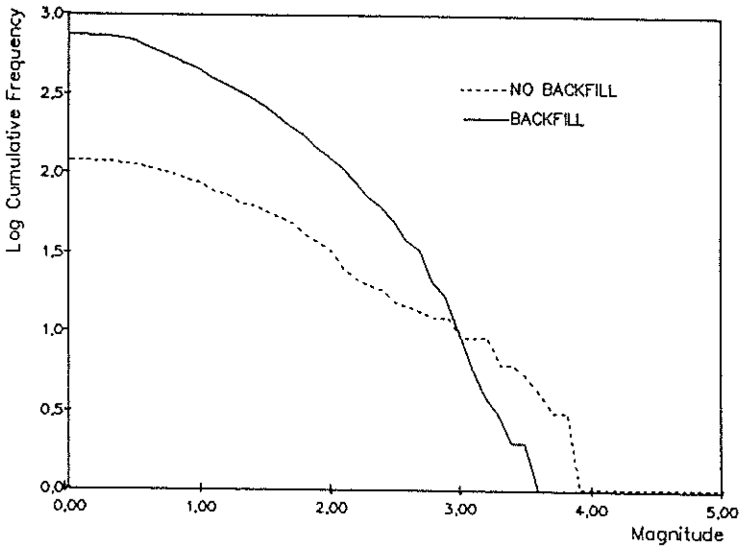

Figure 18 VAAL REEFS 2K AREA FREQUENCY MAGNITUDE CURVES

The larger b-value for the period of mining with fill implies a smaller ratio of large to small events. Figure 18 shows the superimposed frequency-magnitude curves for the two time periods. It should be noted that for a large part of the period of mining without backfill, magnitude calculations were based on surface measurements. This meant that events with $M_L < 1{,}5$ were under-estimated.

From the intersection of the curves with the x-axis of the graph it is evident that backfill has caused a reduction in the maximum recorded magnitudes. It has been proposed that the maximum face to total closure distance governs the extent of the positive ESS lobe. With the introduction of backfill, this distance is reduced to the fill to face distance and one would therefore expect an associated reduction in the size of the positive ESS lobe and hence in the magnitude of the largest expected event (Figure 19).

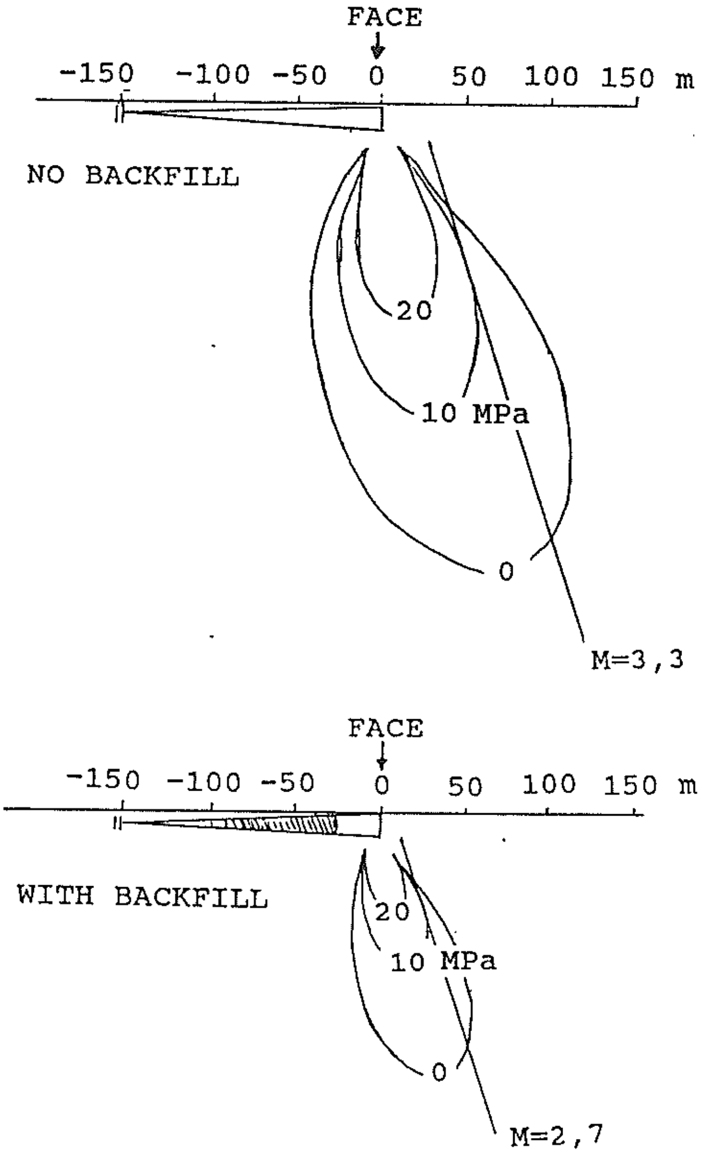

Figure 19 EFFECT OF BACKFILL ON THE SIZE OF POSITIVE ESS LOBES

- A decrease in seismicity at WDL 110-112 level after the introduction of backfill, both in terms of event frequency and event magnitude. The initial γ_M value of 0,21 for this area during mining without fill decreased to 0,12 during mining with fill. A considerable portion of the total seismic energy released was as a result of stabilising pillar failure.

- An increase in both the number of events and the event magnitudes at WDL 113-114 level during the period of mining with backfill. However, the normalized seismicity values in this area after the introduction of backfill was still lower than those recorded in 110-112 level during mining with backfill. Prior to mining with backfill the γ_M value was 0,04. Once again pillar failure contributed a high percentage of the total seismic energy released.

- An increase in seismicity for the period of mining with fill at WDL 83-90 level. Once again this increase was both in the number and magnitude of seismic events. This area also showed a low level of seismicity compared to other areas. The γ_M values before and after the introduction of fill were both less than 0,04. Pillar failure did not contribute significantly to the total seismic energy released.

- An increase in the number of events recorded during the period of mining with fill at Vaal Reef 2K area. However, there was a decrease in the maximum magnitudes and released seismic energy values which indicates that the increase in the number of events occurred primarily in the small magnitude range. This area experienced a high level of seismicity prior to the introduction of backfill. The γ_M value for this period of mining was greater than 2,0.

It is difficult to draw firm conclusions from these data as in many cases different factors were influencing supposedly similar data sets. It is therefore not yet possible to say that backfill is effective in reducing regional seismicity. Ideal data sets are extremely difficult to find and it would appear, particularly on a local scale, that geology and mining layouts have a greater influence on seismicity than the presence or absence of backfill. Pillar failure was found to contribute significantly to the seismicity in a number of areas. It would seem that in areas where :

i) backfill is being placed on a mine-wide basis or
ii) the likelihood of the rock to deform seismically as a result of mining in an area is greater than say 10 per cent (ie. γ_M less than 0.1) prior to the introduction of fill

there is a reduction in released seismic energy. However, more data from such areas would have to be obtained before this could be stated conclusively. In a number of a cases trends in seismicity were found to change according to the time period selected for analysis. This meant that any updates to the data sets could produce contradictory results.

It is recommended that this work be repeated in the future with additional data sets which should cover long time periods in order to minimize the effects of any short term fluctuations in trends.

The γ_M value is significantly smaller for the period of mining with fill, suggesting that the introduction of backfill has reduced the likelihood of the rock to deform seismically. The large γ_M value for the period of mining without backfill was largely a result of the magnitude 4,9 event which occurred on the boundary of this data set. Mining areas are most conveniently chosen as the areas between large faults, while seismogenic regions cover the large faults and the areas around them. The magnitude 4,9 event may therefore have occurred as a result of a build up of energy from mining in three different areas.

Figure 20 shows the maximum magnitudes recorded during each time period. It is evident that the maximum magnitudes recorded have decreased since the introduction of backfill and have also stabilised in that there is very little variation in the values recorded over the last three years.

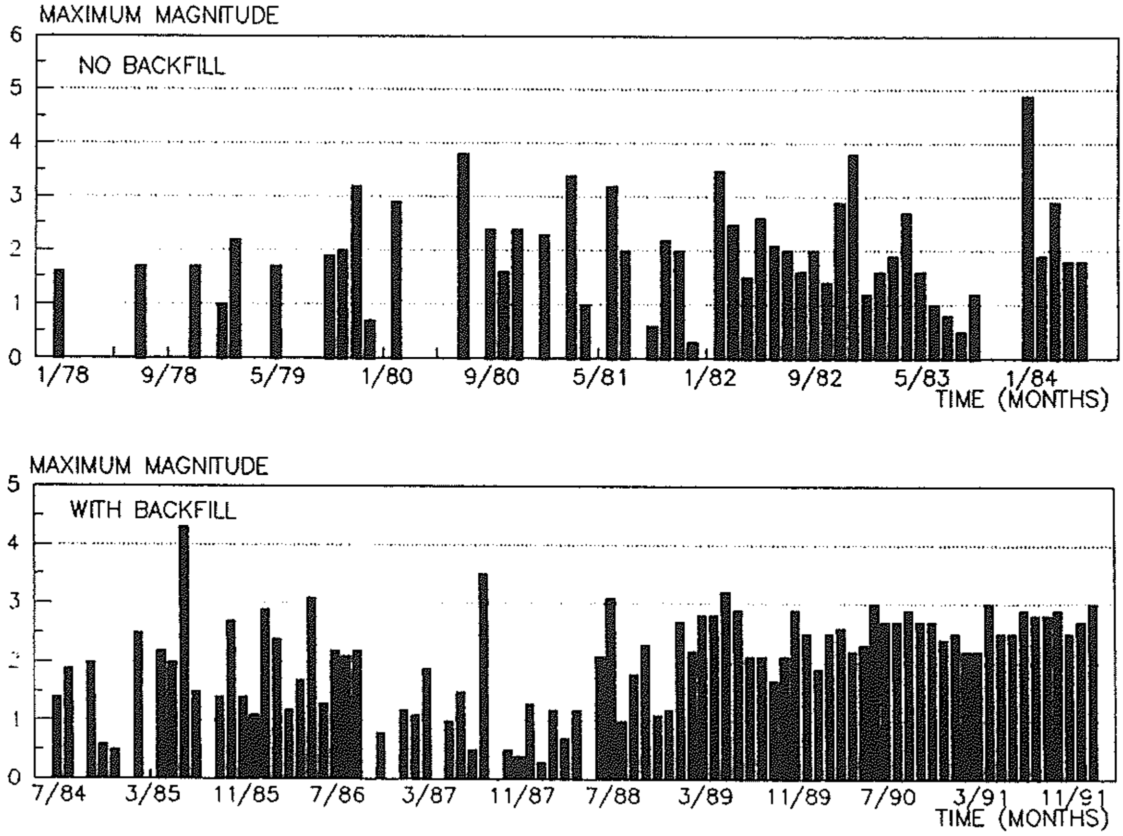

Figure 20 VAAL REEFS 2K AREA MAXIMUM MAGNITUDES

These results are all consistent with previous results obtained from this area.

4 CONCLUSIONS

Analysis of the data has shown:-

5 ACKNOWLEDGEMENTS

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APPENDIX I

SEISMIC EQUATIONS

Calculation of Frequency Magnitude Statistics

The frequency magnitude statistics are the values a and b in the equation :

$$\mathrm{LOG}\ N(M) = a - bM$$

where N is the number of events with magnitude greater than or equal to M. The parameters a and b are computed by the maximum likelihood method, ie the formula derived by Utsu (1965) in a form given by Aki (1965) is used:

$$b = \mathrm{LOG}(e)/(M_{ave} - M_{min})$$

where LOG(e) is approximately 0,4343, M_{ave} is the average magnitude and M_{min} is the smallest magnitude that is detected with '100 per cent' certainty by the network.

The a value is calculated according to:

$$a = \mathrm{LOG}[N(M_{min})] + b$$

where $N(M_{min})$ is the number of events with $M > M_{min}$.

The uncertainty in b can be calculated at the 90 per cent confidence level from:

$$\sigma = 1.96\,b / (N)^{1/2}$$ Aki (1965)

Calculation of γ Values

McGarr (1976) presented a method for equating the elastic change in volume due to mining, ΔV_E, with the seismic deformation due to the volume change. This relationship was written as:

$$\Sigma M_0 = \gamma_E G\ [\Delta V_E]$$ McGarr (1976)

where ΣM_0 is the sum of the seismic moments of the population of seismic events and G is the rigidity or shear modulus. The factor γ_E is the ratio of cumulative seismic moment to volumetric moment, meaning that it is a direct measure of the seismic deformation associated with elastic closure due to mining. Like the b value, it is probably a function of geological conditions.

Assuming an average stoping width of 1 m, the area mined can be taken as a measure of volume change, ΔV_M. Strictly speaking, this leads to γ_M values. The γ_E and γ_M values are related by the following equation:

$$\gamma_E = (2\gamma_M ERR)/\sigma_V$$

where ERR is the elastic energy release rate and σ_V is the overburden pressure.

Following Webber (1989), γ_M values were calculated in this report through the use of the total areas mined in Tables 1, 4 and 7 to obtain ΔV_M.

It can easily be shown that

$$\Sigma M_0 = 20000 \Sigma E$$

where ΣE is the total seismic energy released. Therefore

$$\gamma_M = 20000 \Sigma E/(G \Delta V_M)$$

It is possible that γ is a parameter which indicates the likelihood of the rock to deform seismically during the relaxation of deviatoric stresses in a volume of rock. Also, a γ value greater than one means that the seismic energy generated by the system is greater than the energy induced by the mining. This implies that the pre-mining stress field was sustained by the cohesive strength of the rock, ie there were areas of positive ESS prior to mining.

The average rigidity modulus used in this analysis is $3{,}0 \times 10^{10}$ N/m^2.