The Extraction of Existing Remnant Blocks of Ground at Harmony Gold Mine's Free State Operations

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Declaration

I declare that the research report is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

Signed this __________ day of ________________________ 2008

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P J Le Roux

Executive Summary

Twenty four percent of mining in the Free State region that is currently being done by Harmony Gold Mining Company Limited is remnant extraction. Remnants were often left in the past along geological structures that were known to be seismically active or un-pay blocks of ground. The decision as to the extent and sequence of extraction of these areas can be quite complex. The optimum mining sequence currently takes rock engineering criteria such as energy release rate, average pillar stress, excess shear stress on fault planes as well as seismic activity into consideration.

The question arises whether these criteria are actually useful in evaluating remnants. In this study it was decided to evaluate average pillar stress, energy release rate, the Mohr-Coulomb failure criterion and hydraulic radius (area of remnant / perimeter of remnant) as criteria and analyse the remnants to see if there are any meaningful trends. To determine which remnants should be used for the study in the Free State region, it was decided to evaluate remnants which had adequate seismic coverage and history. In the Free State region it was found that there were only two shafts, Harmony 2 Shaft and Bambanani Mine that satisfied these requirements.

Ten remnants were identified on the mentioned shafts, where problems such as serious injuries and loss of access ways or equipment due to rockbursts occurred, enabling the author to evaluate certain rock engineering criteria that could be used to reduce the hazard of such incident(s) occurring. Back analyses were done on these case studies, comparing the rock engineering criteria mentioned above.

From the results it was found that average pillar stress, energy release rate and hydraulic radius are not suitable criteria for the evaluation of remnants. The results indicated that 93% of the case studies failed violently before reaching an average pillar stress of 450MPa and that 82% of the case studies failed violently before reaching an energy release rate of 30MJ/m^2, if assuming seismic events indicate remnant failure.

Comparing the number of seismic events with a local magnitude, $M_L \geq 1.5$, it was found that there was no correlation between seismic events and hydraulic radius. From the study it seems that remnants >5350m^2 are most seismically active with a sharp drop in seismicity when smaller than 5350m^2. It was, however, found that the Mohr-Coulomb failure criterion delivered more realistic and useable data. Using the Mohr-Coulomb failure criterion [31]

$$\sigma_1 = q\sigma_3 + \sigma_C$$

where $\sigma 1$ and $\sigma 3$ represent, respectively, the major and minor principal stresses, σ_c and q represent, respectively, the rock mass uniaxial compressive strength and slope of the best fit-line.[31] From the back analyses, a criterion for the safe extraction of remnants is proposed. This guideline will only apply to mining of remnants in the Free State region. [31]

When analyzing the σ_1 and σ_3 results obtained within the remnants at the time of each seismic event, it was found that there is a strong correlation between the stress states, which can be described by the following remnant evaluation criterion [31]

$$\sigma_1 = 2.12\ \sigma_3 + 5.56$$

If one calculates the difference for σ_1 between the stress states for each seismic event and the linear trend line, and then take the mean of these errors, it will be found that the mean error in prediction of σ_1 can be determined. The mean error in prediction of σ_1 was approximately 45MPa, giving a coefficient of variation of 17%, which was considered an acceptable variability.[31]

To evaluate remnants for possible violent failure the following Remnant Failure Index (RFI) based on the Mohr-Coulomb failure criterion is proposed for the Free State region.

$$RFI = \frac{\sigma 1}{1.7\ \sigma 3 + 7.9}$$

When the $RFI = \frac{\sigma 1}{(1.7\sigma 3 + 7.9)}$ is greater than 1 the remnant will fail violently.

When the $RFI = \frac{\sigma 1}{(2.5\sigma 3 + 27.9)}$ is greater than 1 the case study results show that violent remnant failure no longer occurs.

The newly developed Remnant Failure Index enables the practitioner to model proposed mining layouts for the remnant and identify possible areas within the remnant where failure can occur and the mining step at which it is expected to happen.

Dedication

This project is dedicated to my family with special mention to my wife, Ronel, who has been very supportive during my preparation of this document. My family's understanding and patience over the two year period is truly appreciated.

Acknowledgements

The author would like to thank Harmony Gold Mining Company Limited for the privilege of presenting this report on remnant being mined within the Harmony Gold Mining Company. The permission to include data and make use of equipment, as well as the assistance received from my colleagues at Brentley, Lucas & Associates, Mining Consultants, is greatly appreciated. In addition, great thanks to Dr. M Pretorius and Dr. T. D. Wiles for the support received regarding assistance and MAP3D-SV.

Table of Contents

List of Figures

List of Tables

List of Graphs

List of Symbols

σ_1	-	Major principal stress in MPa
σ_3	-	Minor principal stress in MPa
σ_v	-	Vertical component of virgin stress expressed in MPa
σ_t	-	Tensile strength of the rock in MPa
σ_c	-	Uniaxial compressive strength (UCS) of rock in MPa
E	-	Young's modulus in GPa
ν	-	Poisson's ratio
c	-	Cohesion in MPa
φ	-	Angle of friction in degrees
ρ	-	Relative density in kg/m^3
APS	-	Average pillar stress in MPa
ESS	-	Excess shear stress in MPa
ERR	-	Energy release rate in MJ/m^2
M_{max}	-	Maximum magnitude (seismology)
M_L	-	Local magnitude (seismology)
S_m	-	Effective stoping width in meters

1. Introduction

"With a fresh look we can start to recognise the unlimited opportunity that lies all around us. We must look to the present and future. We must see the oak while it is in the acorn, the flower while in the seed and the spark while it is in the flint."[61]

As gold mining resources in the Free State are being depleted the Gold Mining industry is forced to re-evaluate their operational, financial and strategic objectives so as to extract gold more economically at lower grades. As a result, most of these low-grade areas were found to be profitable again to pursue. Twenty four percent of the mining that is being done by Harmony Mine in the Free State is remnant mining.

Some of these remnants were left in the 1960's where the surrounding area is mined out extensively. The areas left were either as the result of longwalls intersecting a geological structure with significant displacement, the final remnant left at the lowest point of access or un-pay blocks of ground.

Early in the mining history of South Africa it was identified that remnants needed special precautions when being mined. Before any design criteria for remnants can be evaluated, the history of remnants should be discussed, highlighting the significance of these areas and changes in mining considerations from 1924 to present. There is a negative connotation to the word "remnant" in the mining industry, due to the number of incidents that occurred at these areas.

Chapter 2 will deal with the historical review, layout design and remnant extraction methods currently used in South Africa. In this chapter the difference in definitions and mining considerations used will be highlighted and a brief overview of the history of gold mining in the Free State region will be given.

In Chapter 3 the process for evaluating remnants for mining, layout considerations and support recommendations when mining remnants in the Free State will be discussed. The different types of remnants found will also be discussed briefly.

Geology always has a major influence on the behaviour of the rock mass. To provide some information on this important topic, the geological succession in the Free State will be described in Chapter 4, highlighting the difference in the hangingwall and footwall formations, and comparing them with corresponding formations in the Witwatersrand area. The material properties of the hangingwall and footwall formations in the Free State will briefly be discussed.

The evaluation of stability and behaviour of remnants requires the definition of evaluation criteria. Several possible criteria have been identified, and these are introduced in Chapter 5. In this chapter, the background and theory associated with the criteria will be dealt with briefly.

In Chapter 6 the selection of remnants for case study analysis, and the modelling methodology will be discussed. The seismic history associated with the remnants will be considered, with emphases being placed on the number of events that were recorded for different local magnitudes, and on the diurnal distributions of these events.

Chapter 7 will present the analysis of the results obtained from the case studies, comparing these results with those currently used in the mining industry. Based on the case study results, a new remnant evaluation criterion was developed for the evaluation of remnants in the Free State. This chapter will also discuss how the newly developed Remnant Failure Index can be applied when evaluating remnants.

2. History of Remnant Mining

This chapter deals with the historical review, layout design and remnant extraction methods used in South Africa. It also deals with the difference in definitions and mining considerations used and a brief overview of the history of gold mining in the Free State region will be given.

2.1. History of Mining in the Free State

The earliest mention of the discovery of gold in South Africa was when Carel Kruger in 1834, during a hunting expedition to the interior of the Witwatersrand, took a sample of the ore back to Cape Town. [19]

It is believed that in 1896, Donaldson and Hinds, a prospector and engineer respectively, investigated a portion of the farm called Zoeten-Inval for gold bearing ore. This farm belonged to Klopper near where the town of Allenridge is situated today. Here they excavated an 18m pit and collected samples, which they presented to the mining companies in Johannesburg. [55]

These mining companies showed no interest in the idea of gold bearing reef in the Free State. The men decided to return to England to have their samples analysed and then to raise capital for the continuation of their search. Unfortunately the ship Drummond Castle on which they where sailing back to England, sank in the Bay of Biscay off the coast of France with the loss of all aboard. [55]

In 1904, Megson widened and deepened the original pit to about 30m and took some samples of the exposed strata away with him, as these indicated some promise of gold. Also, he could not convince the mining companies in Johannesburg of the idea of gold bearing reef in the Free State. For many years Megson tried to convince the mining companies with his samples, until October 1932, when he presented himself to Roberts, a prospector, and Jacobs, a young attorney. [55]

Roberts and Megson went back to Odendaalsrus to inspect the pit and collected new samples for analysis. These samples were analysed by Milne, an Analytical Chemist at the University of the Witwatersrand. These samples indicated that they were definitely gold bearing. The first prospect borehole was drilled on 5 May 1933 and intersected lava formations at a depth of 829m and a number of gold bearing reefs one of which contained fair gold values, but not incentive enough to attract financial assistance. Unfortunately, Roberts was not able to raise any capital and the drilling was discontinued. [55]

Early in 1933, within the Klerksdorp area the Anglo American Corporation, with deep boreholes proved the existence of gold-bearing reef, which soon led to the opening of the Western Reefs Mines. The fact that gold was found in payable quantities in this area led to geologists and those with vision to look beyond the Vaal River into the Free State region. As prospecting was intensified over a wide area in the vicinity of Odendaalsrus, the first high gold value was found in the no.5 borehole, known today as the St. Helena Mining Lease. [55]

In 1946, the borehole known as Geduld 697 yielded good values followed by the phenomenal results of Geduld no.1 borehole and nine months later by Geduld no.2 borehole, leading to thirteen separate mining properties being delineated within the new goldfields area. This gave rise to the development of a new town, Welkom, where six of the mines were situated. St. Helena mine was the first mine to come into production with the first bar of gold in the Free State being poured by Anderson, chairman of Union Corporation, on 26 October 1951. [55]

2.2. History of Remnants

In the early 1900's it became apparent that blocks of ground left along geological structures or as a result of the mining configuration needed to be defined, classified and declared as it was found that there was an increase in the number of rockbursts and mining problems associated with these blocks of ground.

A committee, the "Witwatersrand Rockburst Committee", was appointed in 1924 to report on the occurrence of rockbursts and the control thereof. The Witwatersrand Rockburst Committee published a report that was presented to Parliament in 1924. In this report a rock burst was defined as phenomenon known as "Pressure Burst," "Air Blast," "Strain Burst," "Rock Thrust," "Blistering," "Spitting," "Sudden Flaking," "Bumps," "Crumps" and "Quakes," all of which referred to the sudden rupturing of rock in situ not caused intentionally by tools or explosives. These phenomena would occur in the solid, newly opened stopes, stope faces, stope pillars, dykes, sides of a level, drive pillars, working shafts, remnants and or faults.[19]

2.3. Definition and Declaration of a Remnant

The definition of a remnant as per Oxford English Dictionary is as follows:

"That which remains or is left of a thing or things after the removal of a portion; the remainder, rest, residue. Now applied only to a small remaining part". [26]

During the period 1924 to 1943, a remnant was known as a block of ground or ore left during the mining stage for one or other reason. Remnants and pillars were classified as having the same generic problems associated with them. It must be noted that remnants are blocks of ground left due to mining difficulties or poor grades while pillars are designed for a specific purpose. At that time, remnant mining and reclamation of pillars were regarded as one and the same. [20]

Hill [20] described his definition of a remnant as "not being hard or fast". It is usually a portion of unstoped ground separate from the main body of ore and of such a size that the stresses accumulating in it may result in a pressure burst. The practice was to declare any island of ground a remnant when it reached a size of 1000fms (3344,5m^2) or less. [20]

Pressure bursts were known to occur in larger remnants at depths of 5000ft – 7000ft (1524m – 2134m), but increased when the remnant size becomes less than 1000fms (3344,5m^2) as Table 2.1 shows. [20]

Area of remnant measured in fathoms (fms)	Area of remnant measured in square meters (m^2)	Number of pressure bursts			Percentage pressure bursts for various sizes of remnants
		Central West Shaft	Hercules Shaft	Total	
1200 - 1400	4013.4 - 4682.3	4	2	6	4.5
1000 - 1200	3344.5 - 4013.4	4	2	6	4.5
800 - 1000	2675.6 - 3344.5	12	4	16	12
600 - 800	2006.7 - 2675.6	21	4	25	19
400 - 600	1337.8 - 2006.7	19	8	27	20
200 - 400	668.9 - 1337.8	31	15	46	34
0 - 200	0 - 668.9	6	2	8	6
No. of bursts		97	37	134	100
No. of remnants		25	11	36	
Pressure burst per remnant		3.9	3.4	3.7	

Table 2.1 - After Hill [20] showing the relationship between pressure bursts and remnant sizes at ERPM. [20]

Roberts [21] declared unmined areas at Blyvooruitzicht G.M Co as being a remnant when the smallest dimension across the solid was 150ft (45.7m). It was their experience that ground movement was likely to occur when the smaller dimension was less than 150ft (45.7m), although much larger blocks of ground have been declared remnants. [21]

In 1964, the Rockburst Committee went so far as to classify eight different types of abutments, of which remnants are a subset, as shown in Figure 2.1. [11]

a) *Continent abutment*: is of such an area that a line at right angles to the general line of the face extends for a distance of more than 1000ft (304.8m) through unmined ground.[11]
b) *Cape abutment*: is the part of a large abutment that projects with an acute or obtuse angle into an excavated area.[11]
c) *Island abutment*: an abutment surrounded entirely by worked out areas and smaller than a continent.[11]
d) *Strip abutment*: is of an elongated and roughly rectangular shape with a length of at least five times the average width.[11]
e) *Peninsula abutment*: is not in the shape of a cape projecting from a larger unmined area and is smaller than a continent, surrounded by mined out areas in such a way that the width, at the portion where the peninsula joins the unmined area is less than 304.8m.[11]
f) *Isthmus abutment*: Joining two wider abutments.[11]
g) *Pillar abutment*: An island abutment intended to be left in situ, for some specific design reason, for the life of mine or for a lengthy period.[11]
h) *Remnant*: a portion of an abutment, which is judged to be highly stressed and potentially dangerous.[11]

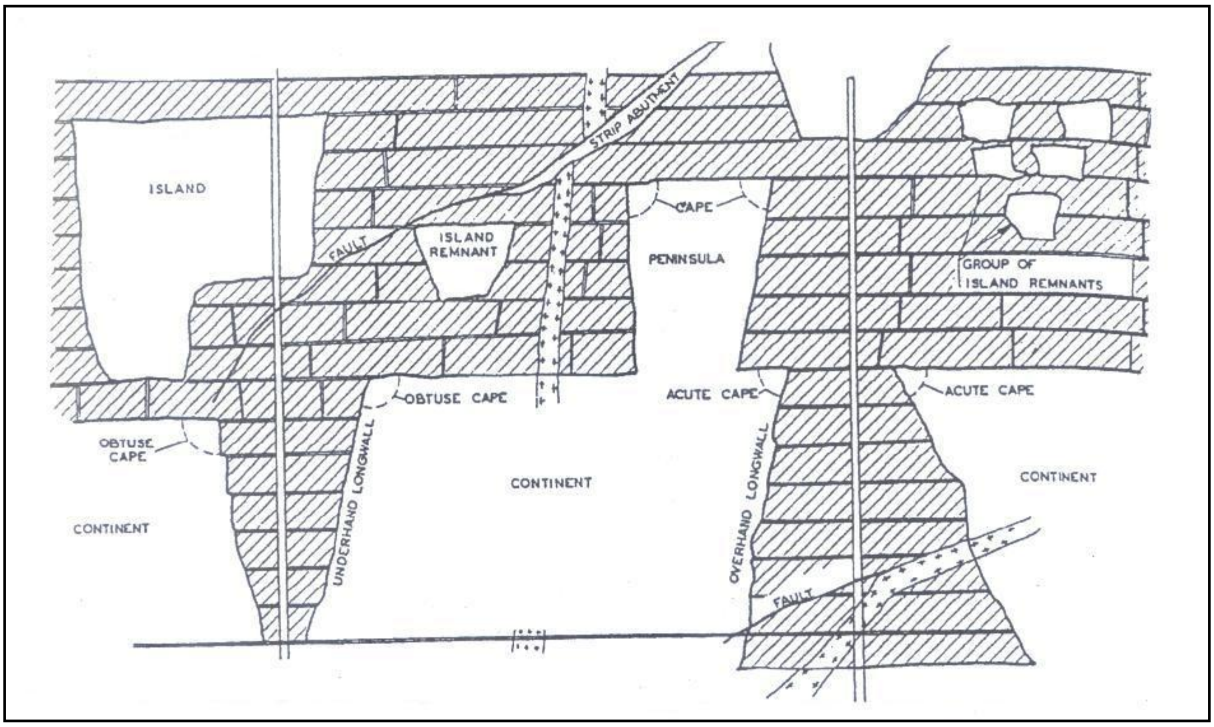


Figure 2.1 - Hill and Denkhaus [11] showing the different types of abutments .[11]

The Commission also issued rockburst precautions according to the size of remnants: [11]

a) It was stated that any portion of ground, not under or over mined, with an area of 1000fms (3344m^2) and less, deeper than 2000ft (609.6m) or shallower than 5486ft (1672m) shall be known as a remnant. These depths were chosen arbitrarily thus knowledge of an area might demand earlier declaration of a remnant. The remnant may be situated between two mined out areas or between a fault or dyke and a working face. In addition, a drive, winze or raise shall be considered the boundary of a block of ground. [11]

b) If one reef was to be mined under or over a solid edge along the dip, the working face will be declared a remnant when the horizontal distance ‘S’ east or west of the solid equals 1.5 times the normal distance ‘N’ between reefs. [11]

$$S = 1.5N$$

c) If one reef was to be mined under or over a solid edge along the strike, the working face will be declared a remnant when the horizontal distance ‘S’ north or south of the solid equals 1.5 times the normal distance ‘N’ between reefs times the tangent of the dip of the reef ‘d’. [11]

$$S = 1.5N \tan d$$

Remnants were classified as follows by the Rockburst Committee appointed by the Government Mining Engineer in 1964: [11]

a) *Listed remnant:* this remnant is considered not to require any special remnant precautions.[11]

b) *Support remnant:* this remnant requires pattern and/or support type modification.[11]

c) *Special remnant:* this remnant requires all possible remnant precautions to be taken.[11]

Van Der Wal and Macaulay [22] declared remnant areas at West Rand Consolidated Mines, Ltd. as follows: “A block of ground is a “declared” remnant when it is anticipated that it will be subjected to excessive pressure and is likely to affect underlying and surrounding workings”.[22]

In the Industry Guide to Methods of Ameliorating the Hazards of Rockfalls and Rockbursts, COMRO, 1988 Edition [24], remnants were defined as: “blocks of ground surrounded by extensive mining, usually created during the final stages of the extraction of a mining area”. [24]

In Figure 2.2 below, the different forms of remnants are shown for longwall mining configurations.

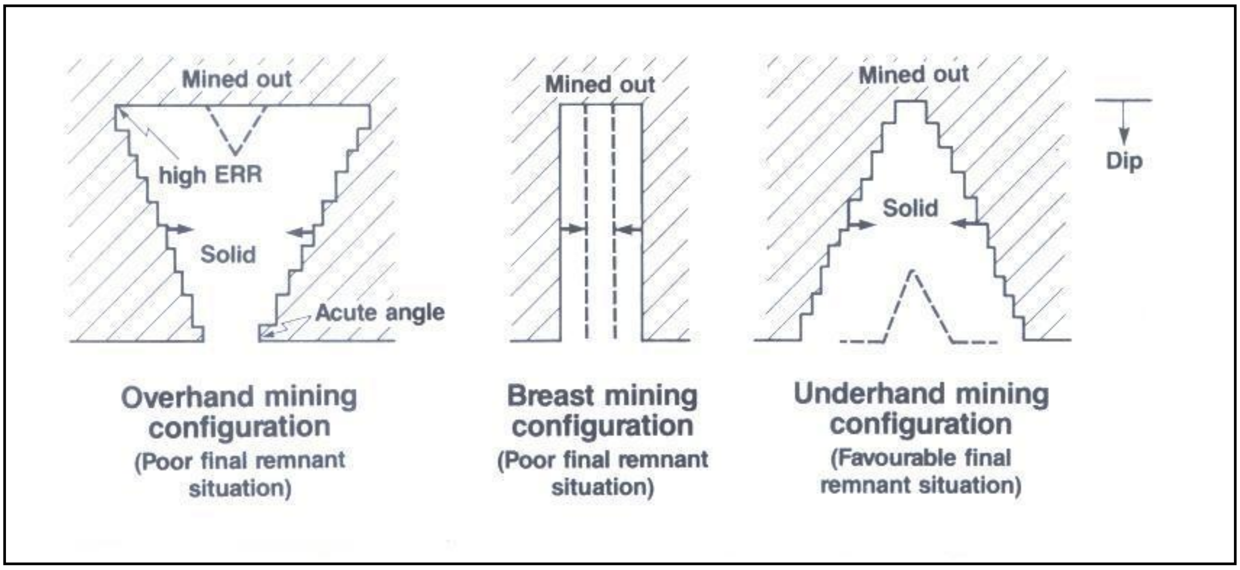


Figure 2.2 - Different forms of remnants depending on the mining configuration .[24]

Rangasamy and Jager [11] suggested that the definition of a remnant should incorporate stress, size and geology.[11]

2.4. Mining Considerations and Remnant Precautions

Over the years alternative mining approaches and precautions practised during remnant mining were introduced. These will be dealt with in this section.

Layout Design

During the 1924 to 1943 period, for reclamation of pillars, which represented remnant mining, precautionary recommendations were made by the Committee in 1924 and are summarized as follows: [19]

General Mining Policy

a) The entire reef should be extracted totally if possible in the first mining stage not leaving any remnants or pillars.[19]
b) On the mine boundaries stoping should be kept well advanced.[19]
c) Stoping should be concentrated at the lowest point of the reef at the mine as far as practicable.[19]
d) When mining two reefs, one of the reef horizons should be mined out in advance of the other.[19]

Stoping out Remnants:

a) The stope face should be blasted every day.[19]
b) Support density should be increased with the aim of withstanding rockbursts.[19]
c) The number of production personnel working at the stope face of the remnant should be reduced.[19]
d) The mining direction should be carefully selected.[19]
e) The stope face should be mined in an underhand configuration.[19]
f) When mining remnants, no stope pillars should be left.[19]

The policy outlined above was followed within practical limits on all mines during this period.

On Crown Mines, special procedures and instructions were laid down for the extraction of pillars: [19]

- Portion A as shown in Figure 2.3 was carried 30ft (9.1m) on the line of true dip.[19]
- The portions A and B were extracted immediately, and two rows of pigsties (pigsties are known as packs constructed from rock) substituted.[19]
- New lines of chutes were provided at intervals of 30ft (9.1m) and the shrinkage support was kept within 6ft (1.8m) of the face.[19]
- Should any portion of the face configuration overhang, it was spragged (a sprag is known as a timber pole installed against stope face) as in Figure 2.4.[19]
- In stage 2 the north and south sidings were completed as in Figure 2.5.[19]
- Pigsties are erected in the chute lines to keep the travelling way open in case of an emergency.[19]
- The holes drilled for blasting were short and the minimum amount of explosives used to minimise blast shock.[19]

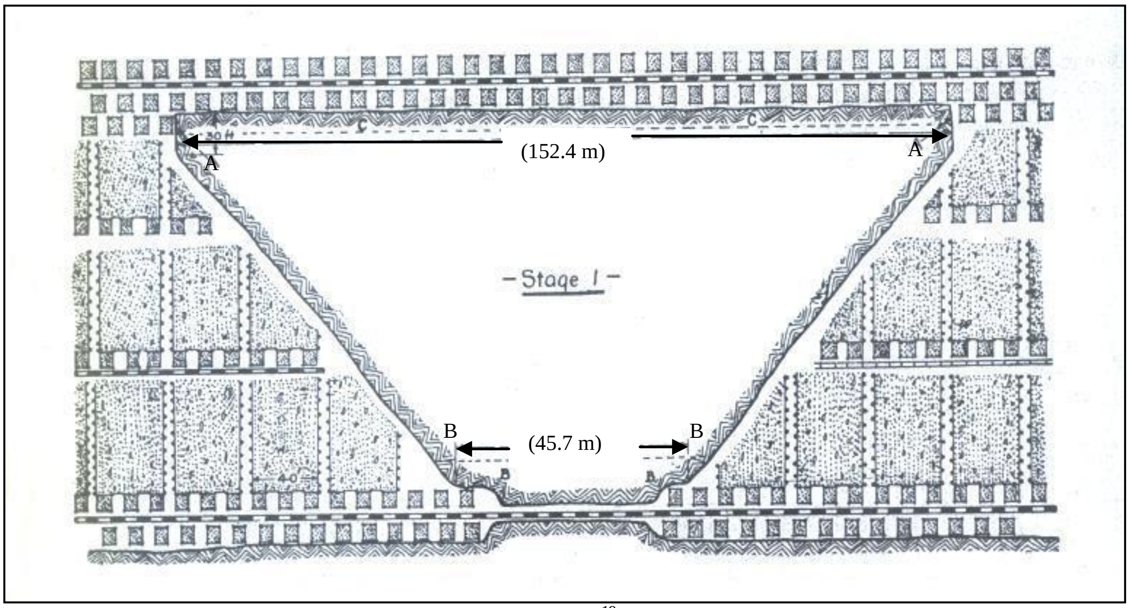


Figure 2.3 - First Stage in the reclamation of pillars, Crown Mines .[19]

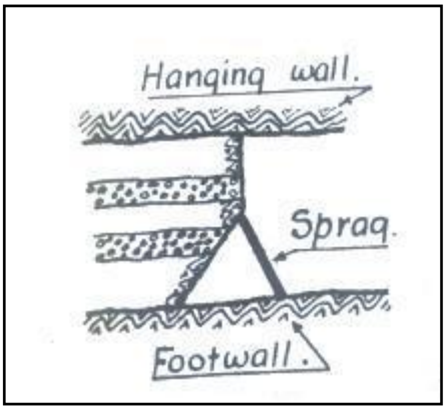


Figure 2.4 - Spragging of face of pillar, Crown Mines .[19]

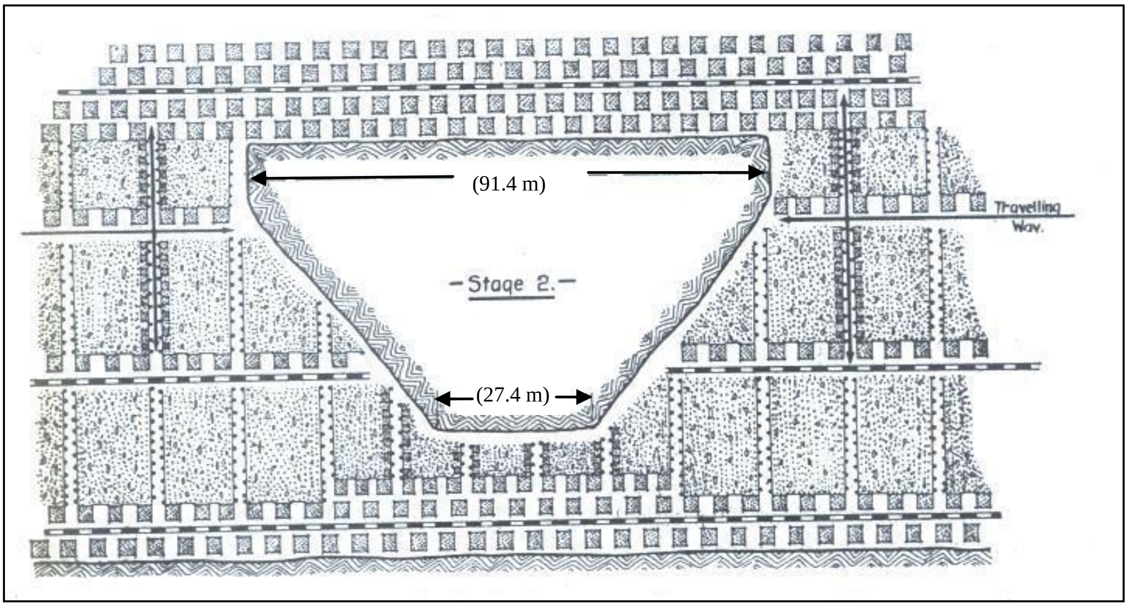


Figure 2.5 - Second stage in the reclamation of pillars, Crown Mines .[19]

- The number of employees was limited to the absolute minimum at the face and only one rockdrill was supplied for each remnant.[19]

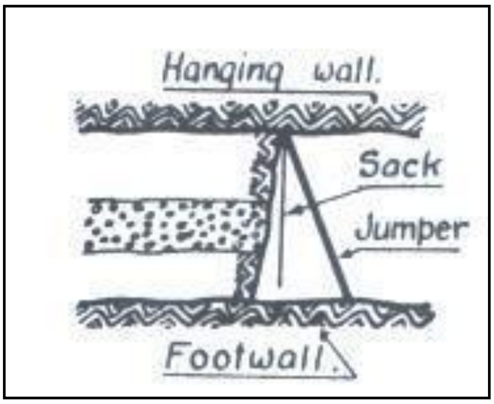


Figure 2.6 - Face of pillar protection with sacks, Crown Mines .[21]

- The practice of undercutting the face was strongly prohibited, and to prevent injuries from “spitting,” sacks were supplied for use, as shown in Figure 2.6.[19]
- As the final stage in the extraction of the pillar was reached, pigsties were erected along the face, and the shrinkage system was stopped.[19]
- These pigsties were built to be no more than 10 ft (3m) apart in the direction of strike and dip, as shown in Figure 2.7.[19]

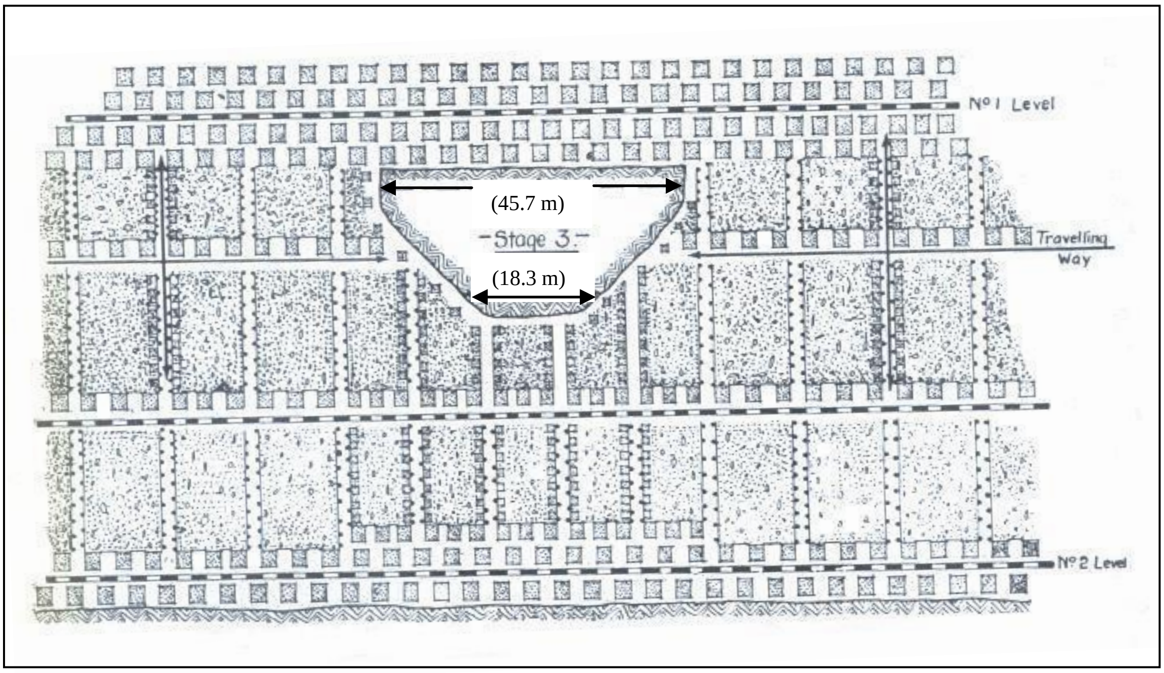


Figure 2.7 - Third stage in the reclamation of pillars, Crown Mines .[19]

Hill [20] stated by doing back analyses during the years 1941 – 1943 that there was a close relationship between the number of remnants being mined and the number of pressure bursts recorded. [20]

It was also stated that pressure bursts in remnants could not be prevented by stope support, rate of face advance, or geometry of remnants. This is demonstrated by the following:

a) *Support*: Figure 2.8 shows eight remnants supported by a complete fill of reef or waste rock, reinforced with slabbed mat packs. Stars indicate the position of pressure bursts that occurred while these remnants were being mined. In spite of the extent of fill support the pressure bursts still occorred.[20]

Complete fill lost favour during this time as large volumes of rock that burst into the travelling and second escape ways impeded rescue operations.[20]

b) *Face advance*: Figure 2.9 shows eight remnants mined at an average rate of 125fms (418m^2) per month, with a face advance of over 25ft (7.6m) per month. Stars indicate the position of pressure bursts that occurred while these remnants were being mined.[20]

It was stated that “speed” or mining rate was not the solution as, although quick extraction gives better hangingwall conditions and reduces the exposure time for men working in the remnant, it places the remnant at risk.[20]

c) *Shape of remnant or direction of face advance*: Figure 2.10 shows different remnants with underhand and overhand faces being mined north, east and west respectively and miscellaneous remnants with dykes and faults.[20]

No statistical data were given as there were too few remnants and too many variables such as shape, direction of face advance of remnant and severity of pressure burst. It was concluded that no matter what the shape or direction of face advance, pressure bursts were inevitable when the block of ground reached the critical remnant stage.

Overhand faces were favoured, not because a smaller number of pressure bursts were likely to occur, but because rescue operations were easier. The general opinion was that the final remnant face should be long, thin, and not shaped like a “pudding bowl”. The theory then was that this type of face shape enabled the stresses building up in the remnant to be dissipated more easily.

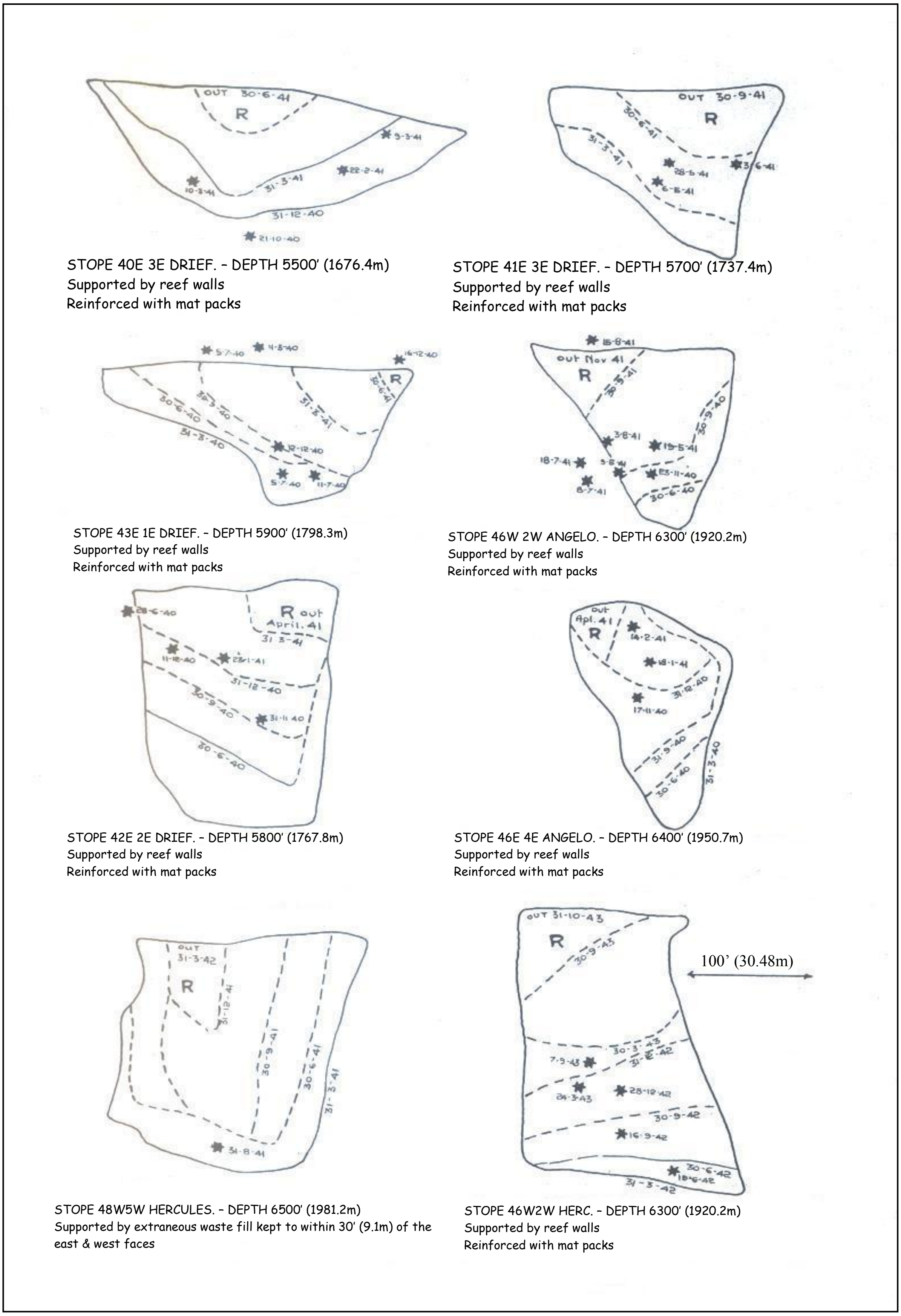


Figure 2.8 - Shows eight remnants supported by a complete fill of reef or waste rock, reinforced with slabbed mat packs .[20]

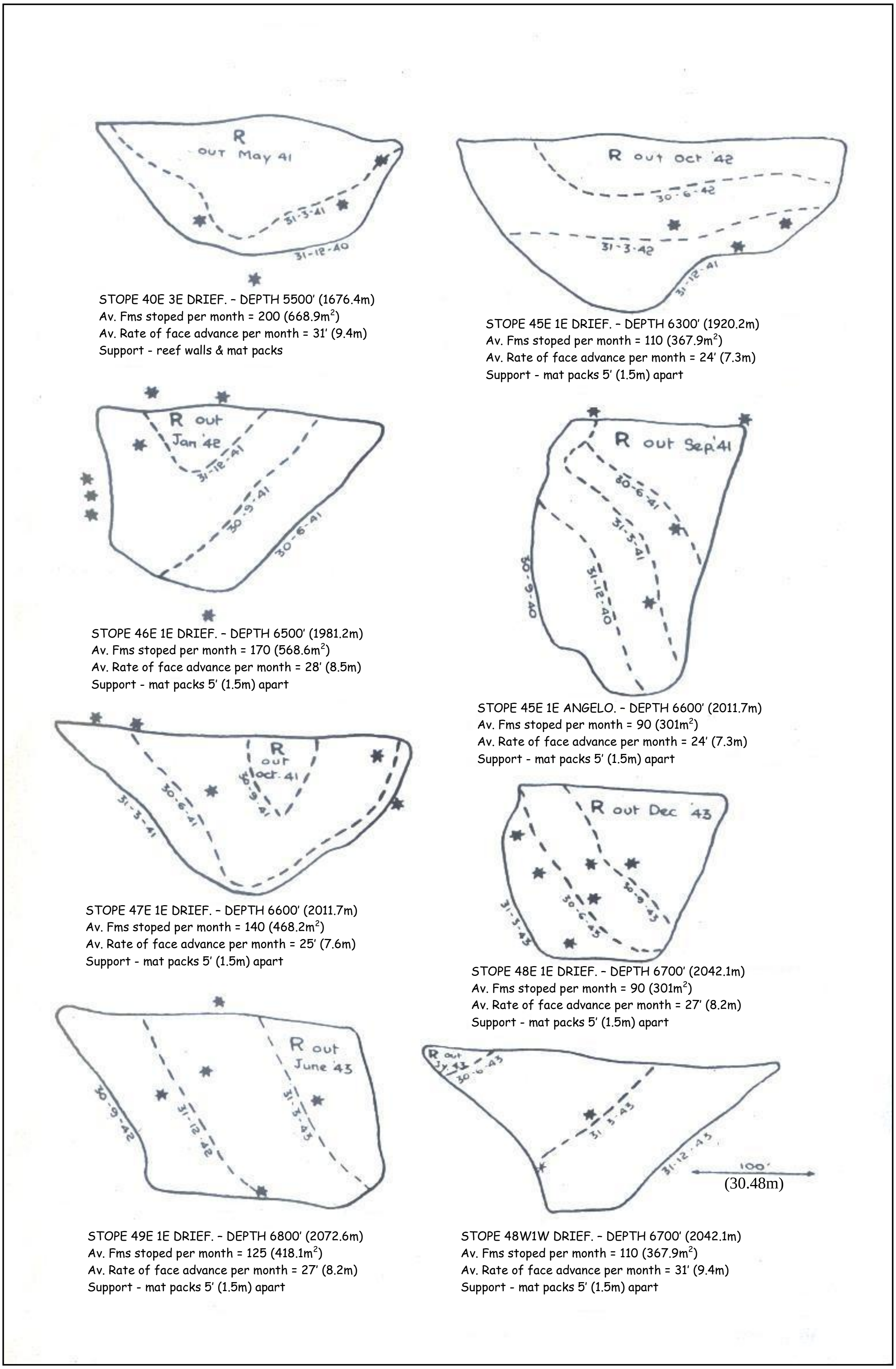


Figure 2.9 - Shows eight remnants mined at an average rate of 418.06m^2 per month, with a face advance of over 7.62m per month .[20]

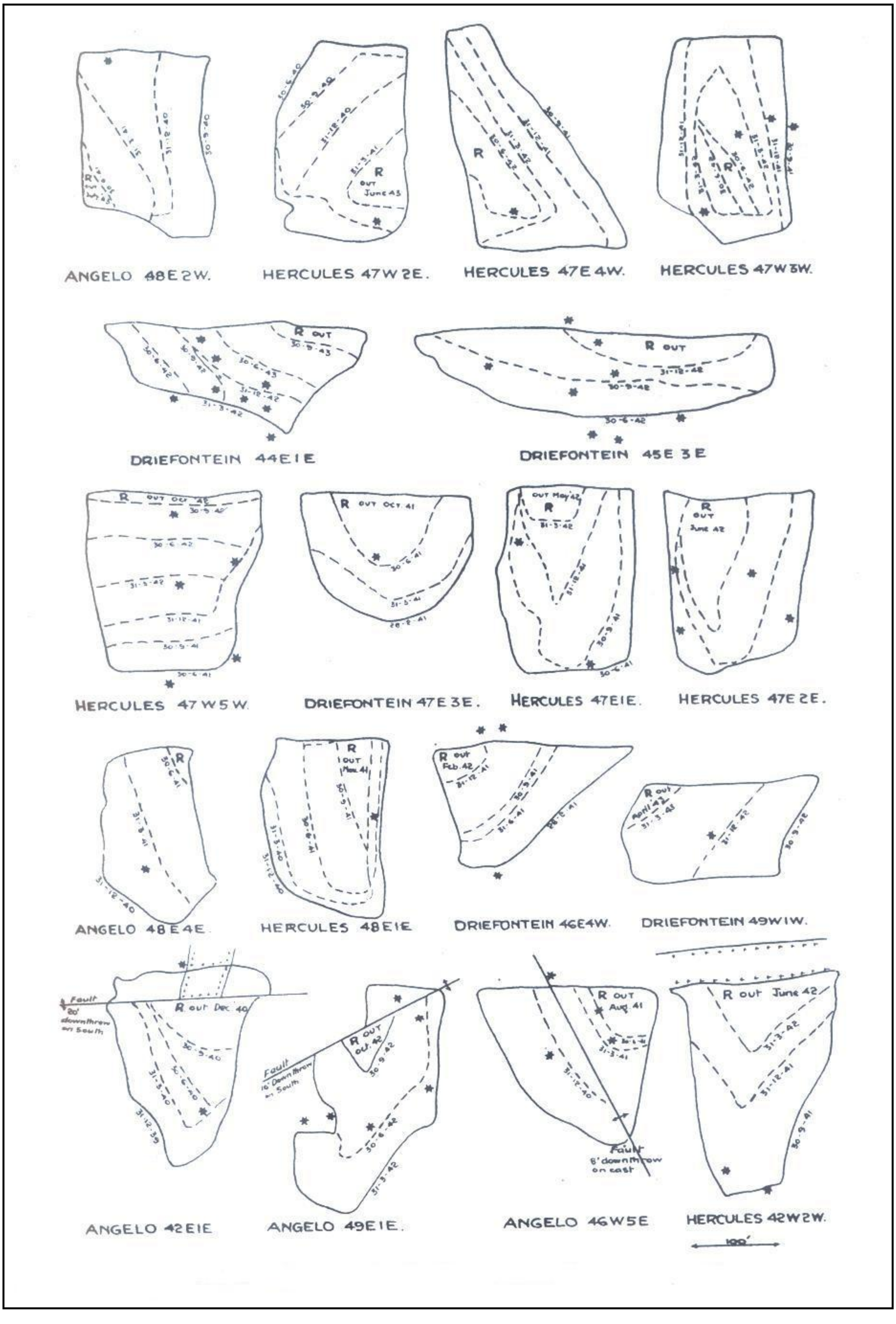


Figure 2.10 - Shows different remnants with underhand and overhand faces being mined north, east and west respectively and miscellaneous remnants with dykes and faults.[20]

In 1964, the Rockburst Committee appointed by the Government Mining Engineer suggested the following layout considerations to be applied to remnant mining: [24]

a) When mining a remnant the layout should be such as to mine towards the largest or closest solid.[24]
b) The layout should be such as to attempt to minimize seismic or ground control hazards, by mining obliquely towards minor geological structures (angle of approach >30°) and by mining away from large geological structures.[24]
c) Remnants should not be split and mined in two different directions. The only exception to this rule would be in shaft pillar extraction. The only acceptable practice for splitting a narrow remnant would be by means of a single heading leaving yield pillars on either side.[24]
d) The panels in the remnant should not approach each other. One side should be stopped and supported accordingly.[24]
e) Leads and lags between panels should be kept to a minimum.[24]
f) Panel faces should be blasted on a regular basis and the advance should not exceed approximately 0.6 times the stoping width. Stoping widths should be kept to a minimum, but not less than 1,1m so as to maintain adequate access after dynamic closure.[24]
g) There should be a second escape way for ingress and egress for each face and these be kept open at all times.[24]
h) For elongated remnants it would be suggested to advance the face in the direction of elongation to reduce the area of positive excess shear stress along faults and dykes, which could reduce the magnitude of seismic activity.[24]
i) It would be suggested to change the direction of mining during the final stage of remnant extraction.[24]
j) Remnants needed to be identified on stope sheets and mine plans to ensure they are given adequate attention during the planning and mining stages.[24]

In the Industry Guide to Methods of Ameliorating the Hazards of Rockfalls and Rockbursts, COMRO, 1988 Edition [24], recommendations were also made regarding the density and quality of support in highly stressed remnants: [24]

a) The dip and strike spacings of the support units in the gully and stope face should be reduced.[24]
b) Permanent support density should be increased to an absolute maximum.
c) Temporary support density should be increased at the stope face area.[24]
d) Umbrella packs, linkbars and/or Headboards to be used to achieve greater support coverage from support to the hangingwall.[24]
e) Permanent support units to be pre-stressed.[24]
f) To introduce rockburst resistant support types such as rapid yielding hydraulic props at the face.[24]
g) Backfill should be considered as this could reduce the effect of rockbursts and improve hangingwall conditions.[24]

2.5. Summary

Hill [20] stated by doing back analyses that there was a close relationship between the number of remnants being mined and the number of pressure bursts recorded. [20] It was also stated that pressure bursts in remnants could not be prevented by stope support, rate of face advance, or geometry of remnants.

The Rockburst Committee appointed by the Government Mining Engineer suggested, when mining remnants, to mine towards the largest solid, to mine obliquely towards minor geological structures and to mine away from major geological structures. Remnants should not be split or mined in two different directions. The leads and lags between panels should be kept to a minimum and elongated remnants should be mined in the direction of elongation.

The Industry Guide to Methods of Ameliorating the Hazards of Rockfalls and Rockbursts, COMRO, 1988 Edition [24], recommended that the support density of permanent and temporary support should be increased when mining remnants.

In the next chapter the process for evaluating remnants for mining, the precautions implemented and the layout considerations enforced when mining remnants in the Free State will be discussed. The different types of remnant found in the Free State will also be discussed.

3. Remnant Mining in the Free State

In Chapter 2 the history of remnant mining in South Africa was discussed, highlighting the transition from the first recommendations made by the Witwatersrand Rockburst Committee appointed in 1924 to the Industry Guide to Methods of Ameliorating the Hazards of Rockfalls and Rockbursts, COMRO, 1988 Edition [24] recommendations. The layout considerations and support to be used in highly stressed remnants were discussed.

This chapter will deal with the process for evaluating remnants for mining, layout considerations and support recommendations when mining remnants in the Free State. The different types of remnants found in the Free State will also be discussed. At Harmony Gold Mines remnants are generally referred to as special areas due to the negative connotations attracted by the word “remnant”.

3.1. Definition of a Special Area

A special area is any block of ground, which has been classed as such by the Shaft Manager or Mine Overseer in consultation with the Rock Engineer. [56]

For a block of ground to be classified as a special area, it must satisfy one or more of the following criteria: [56]

a) The area of the block of ground to be mined must be less than 2400m^2 and its boundary must be defined by worked out areas, geological discontinuities such as faults or dykes, or combinations of these.[56]
b) The physical hangingwall conditions must be such that additional support is required.[56]
c) The mean width of the block in situ will be expected to be less than 30m after the following month’s mining.[56]
d) Stope faces on any reef horizon will approach within 40m of a known seismically active geological structure.[56]

These special areas can be classed as precautionary or restricted. Remnants will normally fall into the restricted category.[56]

3.2. Evaluation Process of Remnants

Before any remnant can be mined there are several key factors that should be considered as shown in Figure 3.1. These factors will include payability, access to the remnant, rehabilitation costs for development, and in-stope support costs for static / dynamic conditions.

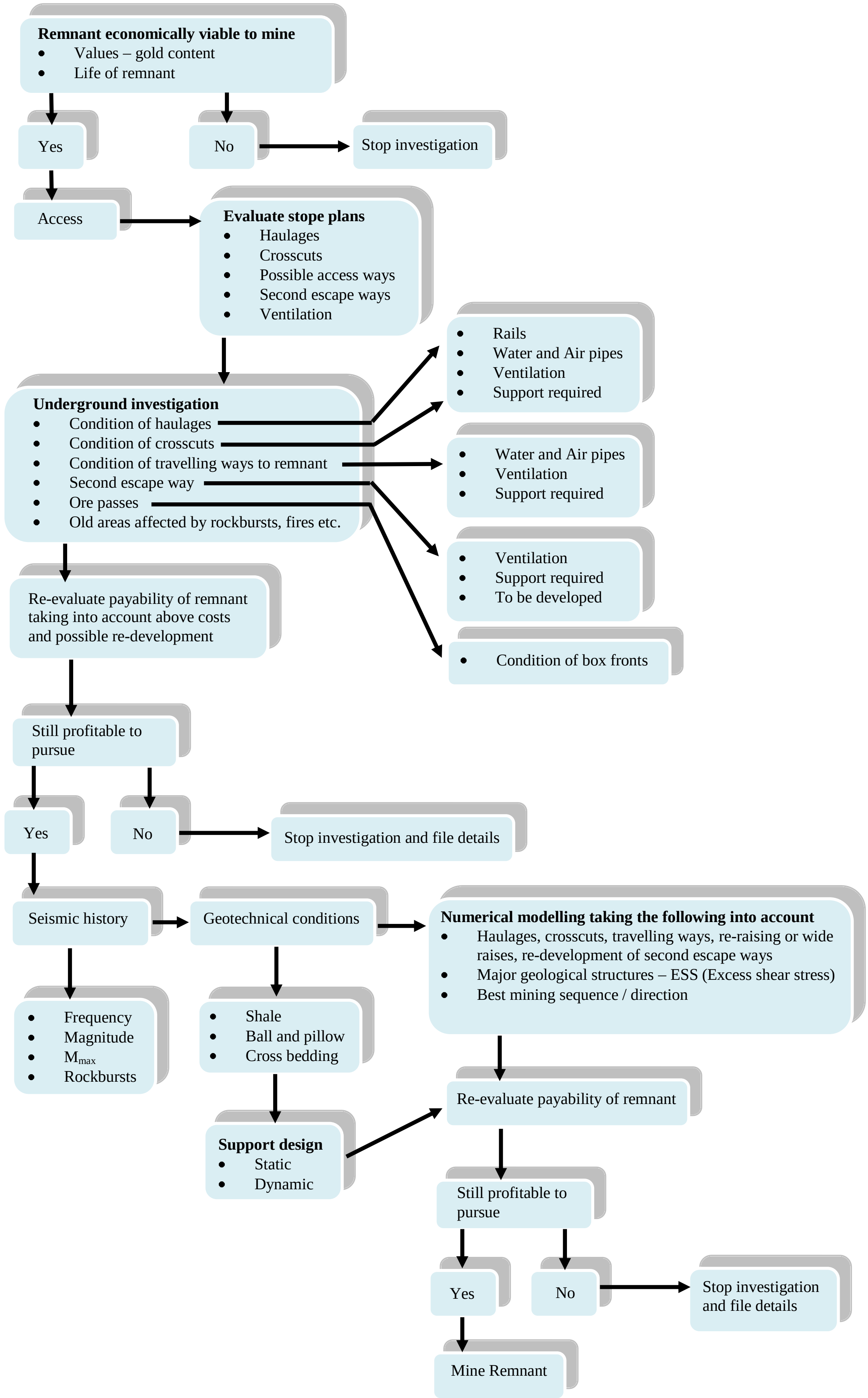


Figure 3.1 - Evaluation process of remnants planned to be mined.

3.3. Layout Considerations and Support Recommendations

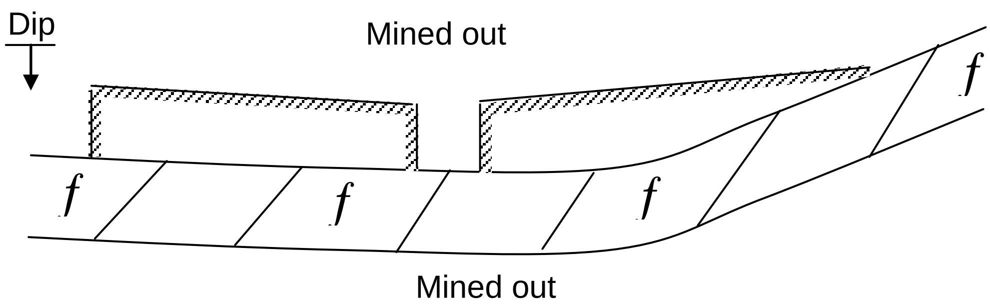
The following are the layout considerations and support recommendations that are applicable to remnant mining in the Free State.[56] These are based on the guidelines presented in the Industry Guide to Methods of Ameliorating the Hazards of Rockfalls and Rockbursts, developed by COMRO [24].

a) The panels shall not approach each other. One panel will be stopped when within 15m of the other panel. [56]
b) As far as possible, mining must take place towards the largest or closest solid. [56]
c) Avoid large lead / lags between panels. [56]
d) Mine away from large geological structures; small geological structures must be approached obliquely, i.e. with an angle greater than 30°.[56]
e) Stope face to be blasted regularly so as to limit time dependent deterioration. [56]
f) Consideration should be given to changing the direction of mining during the final stages of extracting the remnant. [56]
g) The face advance per blast should be kept as small as feasible. [56]
h) Panel face to be preconditioned. [56]
i) The strike and dip spacing of the support units in the face and gully should be reduced. [56]
j) Permanent support spacing to the face should be reduced to an absolute minimum. [56]
k) Temporary support density should be increased. [56]
l) Headboards, linkbars and/or umbrella packs to be used as to achieve greater support coverage of the hangingwall. [56]
m) Permanent support units to be pre-stressed. [56]
n) Larger and/or stiffer support units to be installed. [56]

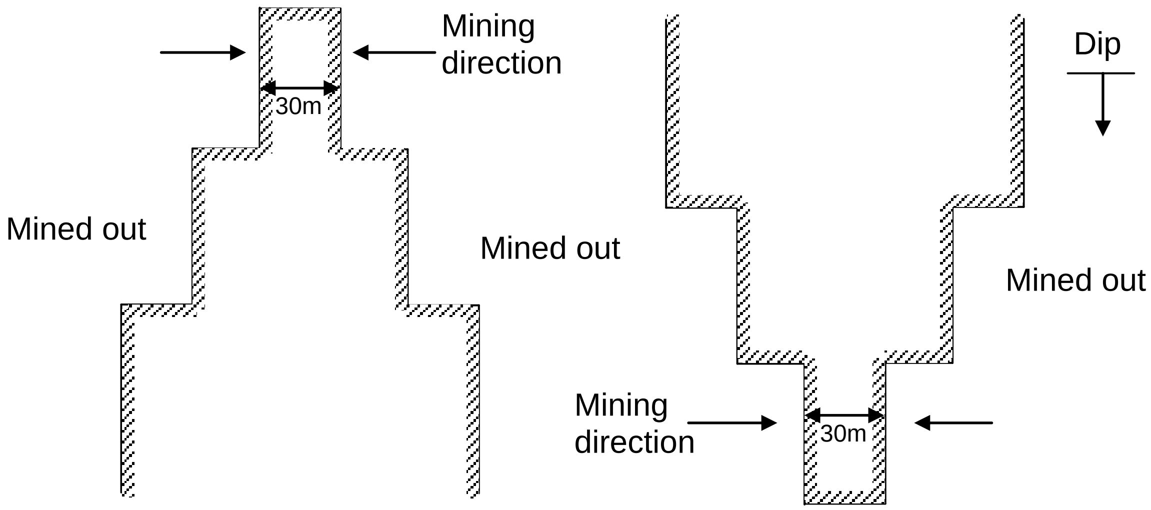
3.4. Types of Remnants in the Free State

Remnants are all different in shape and size, but all share certain characteristics such as being situated along geological structures, bounded by mined out areas, etc. The different types of remnants found in the Free State are listed below.

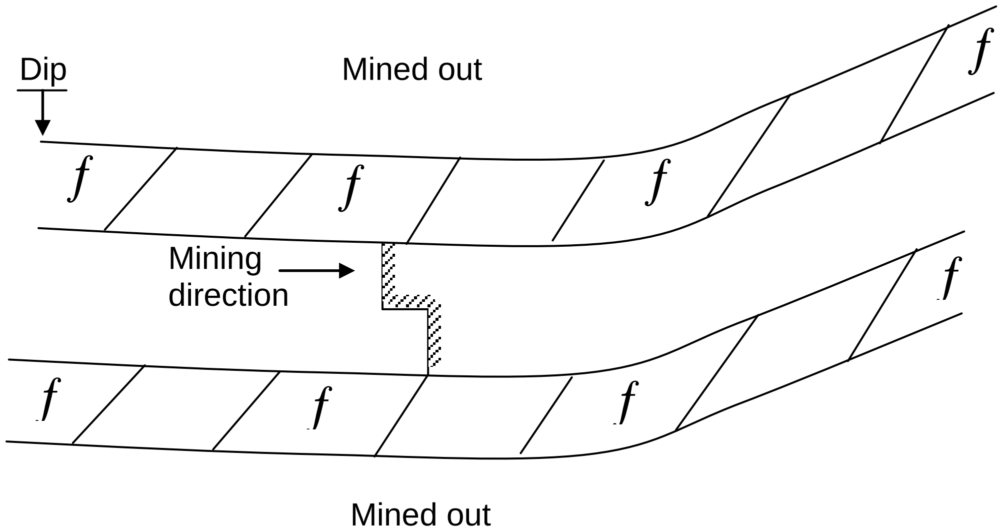
a) Type "A" remnants include remnants situated along major geological structures.



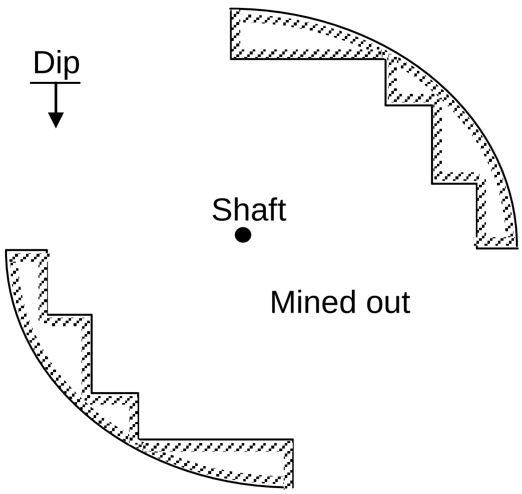
b) Type "B" remnants are those where the mean width of the block in situ will be expected to be less than 30m after the following month's mining.



c) Type "C" remnants are situated between two major geological structures.



d) Type "D" remnants include all remnants mined out extensively all around.



3.5. Summary

In the Free State region remnant mining is unavoidable and will be practised as long as mining continues. The use of the word remnant was made redundant due to its negative connotation; hence remnants are referred to as special areas by definition.

The process for evaluating remnants for mining, support recommendations and layout considerations when mining remnants in the Free State was discussed. The different types of remnant found in the Free State were also discussed in this chapter.

The geological succession in the Free State will be described in Chapter 4, highlighting the difference in the hangingwall and footwall formations, and comparing them with corresponding formations in the West Wits area of the Witwatersrand Basin. The material properties of the hangingwall and footwall formations in the Free State will be also discussed.

4. Free State Geological Setting

In Chapter 3 the process for evaluating remnants for mining, layout considerations and support recommendations when mining in the Free State was discussed. The different types of remnants found in the Free State were also discussed. These will clearly be influenced by the geology and geological structures encountered during mining. The geological conditions in which mining takes place are important with respect to the mining of remnants.

This chapter will describe the geological succession in the Free State highlighting the difference between the hangingwall and footwall formations and comparing them to the West Wits area of the Witwatersrand Basin.

4.1. Generalized Description of the Geological Succession in the Free State

The Witwatersrand Basin shown in Figure 4.1 and Figure 4.2 is the main gold bearing structure in South Africa. The rocks were deposited by sedimentation some 2700 million years ago.[10] The Free State gold bearing reef horizons are situated within the Upper Witwatersrand conglomerates as shown in the geological succession in Figure 4.3. The rocks are made up of quartzite (deposited river sand), conglomerates (deposited river gravels), and shale (deposited mud). The conglomerates have pebbles of chert and quartz with a matrix of quartz gravels, silicates and various sulphides (mainly pyrite).[10]

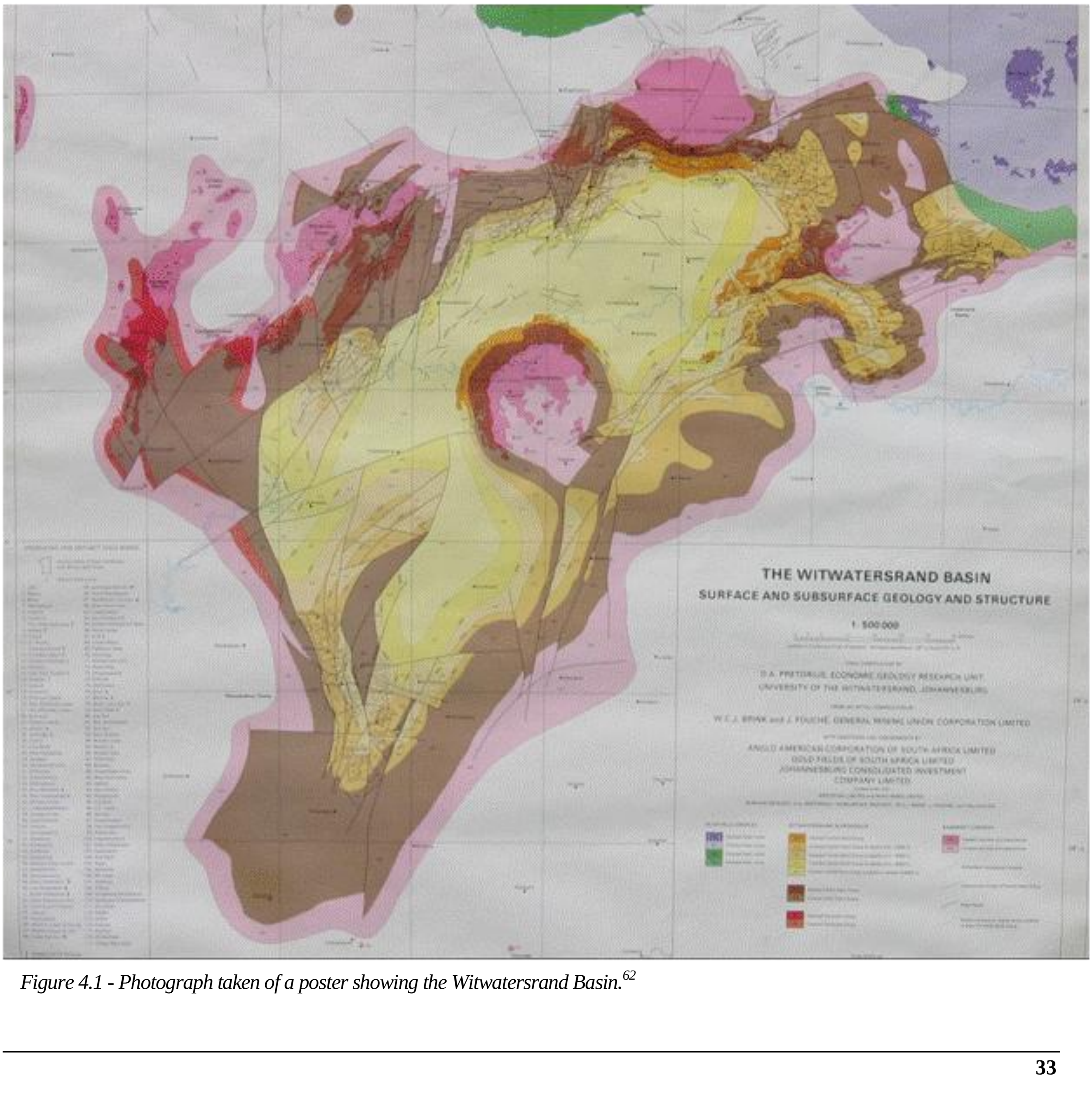


Figure 4.1 - Photograph taken of a poster showing the Witwatersrand Basin.[62]

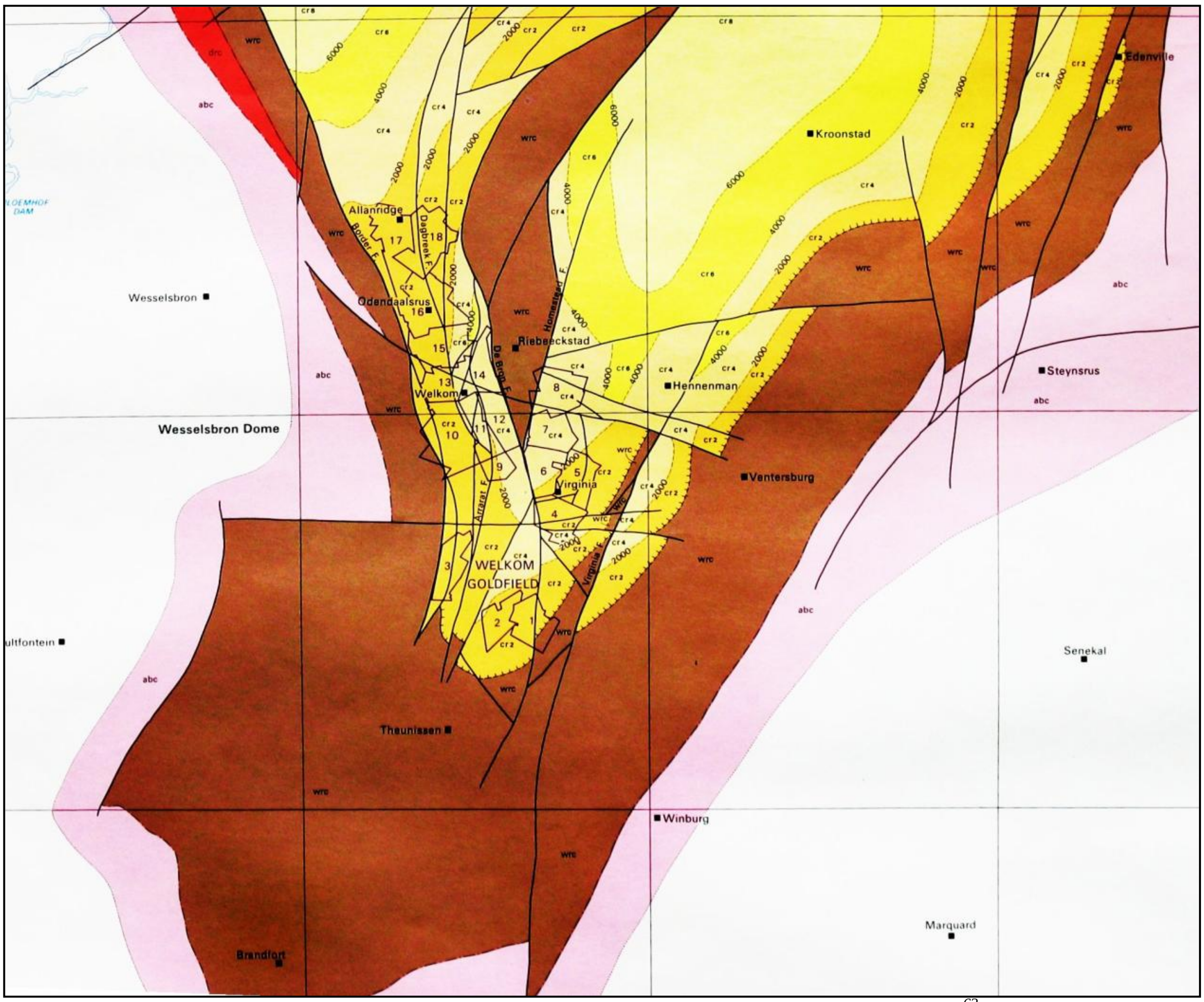
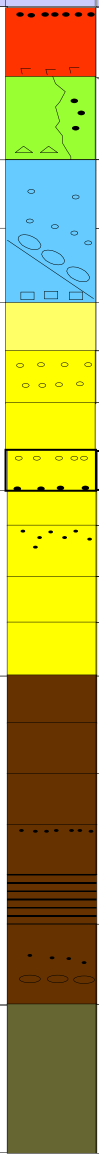


Figure 4.2 - Photograph taken of a poster showing the portion of the Witwatersrand Basin in the Free State.[62]



Supergroup	Group	Sub - Group	Formation	Average thickness (m)	Strat Units	Old Nomenclature
Witwatersrand	Central Rand	Turffontein	Aandenk	14	A Reef BPM	Hangingwall Quartzite
				15 12	Aandenk channel B Reef	
		Johannesburg	Dagbreek	±50	Leader Reef	
			Harmony	15	Middling Quartzite Basal Reef	
			Welkom	76	UF 1	Footwall Quartzite
				75	UF 2	
				60	UF 3	
				10	UF 4	
			St Helena	30	MF 1	
				120	MF 2	
				106	MF 3	
				60	MF 4	
			Virginia	±150	LF 1	
					LF 2	
				500	LF 3	
					LF 4	
					LF 5	
				±150	LF 6 Ada May Reef	
	West Rand			±150		

Figure 4.3 - Stratagraphic section of geology [56]

With reference to the geological succession in Figure 4.3, the section of the Upper Witwatersrand System of relevance to the current research is broken up in the following formations:

- **Harmony Formation**

The Harmony Formation consists of the Waxy Brown Quartzite, Shale and Basal Reef.[10] These are discussed below:

➢ **Waxy Brown Quartzite**

The Waxy Brown Quartzite is generally incompetent with a uniaxial compressive strength of 90 - 240MPa. It is waxy brown in colour and behaves poorly under stress conditions.

➢ **Shale**

The shale is incompetent dark grey to black, which is laminated and is ±50cm in thickness at some areas. This can increase to 6m in the northern areas. The uniaxial compressive strength is 20 - 60MPa.[10]

➢ **Basal Reef**

a) The Basal Reef has a variable nature consisting of light grey, cross bedded, siliceous quartzite with pyrite and scattered buckshot pyrites with thin intercalated polymictic conglomerates, or robust polymictic medium pebble conglomerates with abundant buckshot pyrites.
b) It can also consist of thin oligomictic Basal lag with light grey siliceous quartzite above, or oligomictic small pebble conglomerate overlain by a polymictic medium grained quartzite with occasional gritty phases.
c) Carbon is usually present on the contact.
d) It can also consist of polymictic small pebble conglomerate occasionally with carbon on the contact.
e) The quartzite is siliceous, medium grained with thin grits and pyrite stringers.[10]

The Basal Reef has a considerable variation in lithology and has a uniaxial compressive strength of 140 - 210MPa.[10]

- **Welkom Formation**

The Welkom formation consists of the Upper Footwall Quartzite 1, Upper Footwall Quartzite 2, Upper Footwall Quartzite 3 and Upper Footwall Quartzite 4. Only the Upper Footwall Quartzite 1 of the Welkom formation is discussed since the off reef development leading towards the remnants is situated within this formation.[10]

➢ **Upper Footwall Quartzite 1**

The Upper Footwall Quartzite 1 consists of five zones.

a) Zone 1 is generally a competent, siliceous, grey quartzite, which is poorly bedded and is ±20m in thickness. The uniaxial compressive strength for Zone 1 is 170 - 260MPa.
b) Zone 2 is an incompetent dirty yellow quartzite with numerous bedding planes and is ±15m in thickness. The uniaxial compressive strength for Zone 2 is 100 -150MPa.
c) Zone 3 is also incompetent although less so than Zone 2 being more siliceous and containing fewer bedding planes and is ±15m in thickness. The uniaxial compressive strength for Zone 3 is 200 - 220MPa.

d) Zone 4 is a competent, grey, siliceous quartzite and is ±5m in thickness. The uniaxial compressive strength for Zone 4 is 200 - 220MPa.
e) Zone 5 is an incompetent, grey yellow quartzite with numerous argillite filled bedding planes and is ±25m in thickness. The uniaxial compressive strength for Zone 5 is 190 - 240MPa.[10]

In contrast to this, on Elandsrand Mine, one of the Harmony Gold mines, the Ventersdorp Contact Reef (VCR) is being mined. The Ventersdorp Contact Reef (VCR) is a narrow tabular orebody, which is overlying the Central Rand group and considered part of the Witwatersrand Supergroup. It is overlain by the Alberton Porphyry Formation, an accumulation of porphyritic andesitic lava flows and is 150 – 450m in thickness.[2]

The Alberton lava (igneous formation), which is very competent, with a typical uniaxial compressive strength of 300MPa.[58] The Alberton lavas is overlying the VCR, which are very competent, with a typical uniaxial compressive strength of 250MPa.[58]

Compared with this System, the Upper Witwatersrand System in the Free State is less competent, owing to the Waxy Brown Quartzite forming the immediate hangingwall and a shale layer that overlies the reef in which most of the remnant mining takes place.

4.2. Summary

The Upper Witwatersrand System in the Free State compared to the Carletonville area of the Witwatersrand Basin at Elandsrand Mine, is less competent, owing to the Waxy Brown Quartzite forming the immediate hangingwall and a shale layer that overlies the reef in which most of the remnant mining takes place.

The evaluation of behaviour and stability of remnants in these rocks requires the definition of evaluation criteria. Several possible criteria have been identified, and these are introduced in the next chapter. In Chapter 5, the background and theory associated with the criteria will be dealt with briefly.

5. Criteria Used to Evaluate Remnants

In the previous chapter it was highlighted that the Upper Witwatersrand System in the Free State, compared to the West Wits area of the Witwatersrand Basin, is less competent, owing to the Waxy Brown Quartzite forming the hangingwall and a shale layer that overlies the reef in which most of the remnant mining takes place.

In this chapter the background and theory associated with the criteria will be discussed briefly. To evaluate the behaviour and stability of remnants a definition of evaluation criteria is required. Several possible criteria have been identified, and these are introduced in this chapter.

5.1. Average Pillar Stress (APS)

The concept of average pillar stress evolved from the incorporation of stabilising pillars in the layouts of deep level mining and the evaluation of pillar stability in bord and pillar layouts.[2] The criterion for pillar "punching" into the foundation was developed from physical experiments which suggested that pillar punching occurred at APS $\leq 4\sigma_c$ of the foundation material.[2] However this may range between $3\sigma_c$ and $8\sigma_c$, as suggested by Ryder and Jager [2].

The criterion, APS $\leq f_a\ \sigma_c$, is used extensively in the South African gold mining industry, where f_a is an empirical factor typically taken as 2.5 for foundation failure, and σ_c is the uniaxial compressive strength of the foundation rock material.[2] Failure of pillars and remnants is not necessarily in the form of seismic activity, but can occur aseismically.

5.2. Energy Release Rate (ERR)

Energy release rate is a parameter that is commonly used in the evaluation of mining layouts. Since its introduction in the 1960's it remains to this day the most acceptable parameter for indicating the severity of conditions in deep mining. The average ERR obtained at a given set of mining faces takes into account the effect of depth, mining span, stoping width, rock mass modulus, presence of pillars or backfill, and the influence of adjacent mining.[2]

ERR is a theoretical concept that is based on stress distribution around mining layouts and the displacements resulting from the mining. Elastic behaviour is assumed. The ERR at a face is determined as half the product of the stress in an element at the face and the closure that takes place as a result of mining out that element, mathematically expressed as follows:[2]

$$ERR = \frac{1}{2}\sigma^{\mathrm{P}} S^{\mathrm{t}}$$

where σ^{P} is the absolute normal stress and S^{t} is the convergence.[2] From this it can be seen that ERR is dependent on the elastic assumption. For a lower value of modulus of elasticity E will result in a greater closure being calculated, and hence a greater ERR. Further, if stresses at the face have been relaxed (redistributed) over time, as may occur with old remnants, the validity of the ERR criterion commonly applied may be questionable. These factors need to be considered with regard to the use of ERR as a potential criterion in this research project.

It was suggested that $30MJ/m^2$ is an acceptable average energy release rate value in the design of longwall or sequential grid layouts.[1] It may be found that an ERR value greater than this will have to be considered when mining remnants.

5.3. Excess Shear Stress (ESS)

To evaluate the possibility of slip failure along geological structures, such as faults and dykes, excess shear stress is used. From excess shear stress measured in MPa the magnitude of the expected seismic event can be calculated. Ryder and Jager [2] suggested when evaluating excess shear stress that only the positive shear stress values be used. Ryder [4] defined excess shear stress mathematically as: [4]

$$ESS = |\tau| - \sigma_n tan\varphi$$

where $|\tau|$ is the maximum shear stress on the geological plane, σ_n is the stress acting normal to the plane and φ is the dynamic friction angle. In numerical modelling the dynamic friction angle is usually taken as 30°, but can be as low as 15 - 20° for some "slippery" planes.[4]

Although being one of the criteria used to evaluate remnants in the Free State, for the purposes of this study, excess shear stress will not be used when evaluating the remnants. As mentioned, excess shear stress is used to evaluate geological structures and the obtained results for these structures will be applicable to these structures only.

5.4. Mohr-Coulomb Failure Criterion

In the Mohr-Coulomb failure criterion the shear strength of rock is dependent on the inherent shear strength of the rock material and a normal stress-dependent frictional component. The Mohr-Coulomb failure criterion is mathematically expressed as: [65]

$$|\tau| = S_O + \mu\sigma$$

where σ and τ are the normal and shear stresses, S_o is the inherent shear strength of the rock material and μ is a constant called the coefficient of internal friction of the rock material, mathematically expressed as follows:

$$\mu = tan\varphi$$

where φ is the friction angle as shown in Figure 5.1.

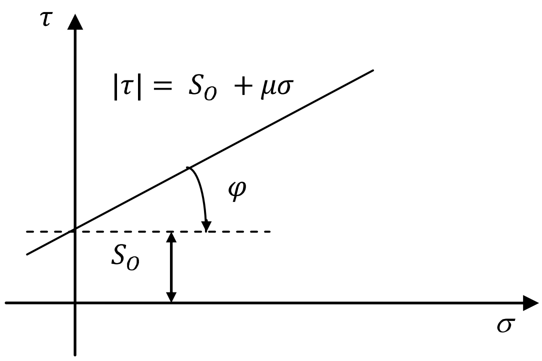


Figure 5.2 - The Mohr-Coulomb failure criterion for shear failure.[65]

The Mohr-Coulomb failure criterion can also be mathematically expressed as: [31]

$$\sigma 1 = q\sigma 3 + \sigma_c \quad (5.1)$$

where $\sigma 1$ and $\sigma 3$ represent, respectively, the major and minor principal stresses, σ_c and q represent, respectively, the rock mass unconfined compressive strength and slope of the best fit-line.[31]

where $q = tan^2(45 + \frac{\varphi}{2})$; φ is the friction angle

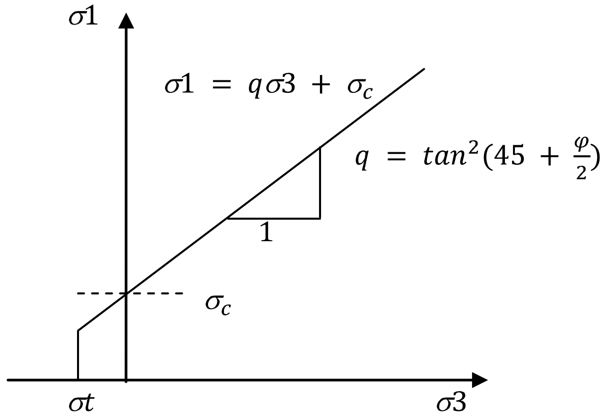


Figure 5.3 - Alternative representation of the Mohr-Coulomb failure criterion.[31]

Equation 5.1 can be used to establish a failure criterion for the failure of remnants where $\sigma 1$ and $\sigma 3$ values are determined for the given seismic event at specific coordinates (x, y and z) and mining steps. From this data a Remnant Failure Index (RFI), based on the Mohr-Coulomb failure criterion, for remnants can then be determined.

Failure is defined as follows:

Where *RFI* = $\frac{\sigma 1}{(q\sigma 3 + \sigma c)}$ and when greater than 1, failure can occur.

The assumption is made that, seismic events occurring in a remnant are an indication that the remnant is actually failing. Only events with a local magnitude, $M_L \geq 1.5$ within the remnant were used in the study. The reason for only using seismic events of this magnitude, is that damage is usually observed.

5.5. Hydraulic Radius

Remnants are generally irregularly shaped making it difficult to compare them with each other as stated by Hill.[20] For the purposes of this study hydraulic radius, also known as the shape factor, will be used. The hydraulic radius of a remnant can be calculated as the area of the remnant divided by its perimeter. Hydraulic radius is predominantly used in massive mining operations where the caveability for a given rock mass with certain geotechnical characteristics is estimated. [63] Since hydraulic radius takes into account the irregular shape of remnants, it was considered as a possible criterion for the evaluation of remnants.

5.6. Summary

The theory on average pillar stress, energy release rate, excess shear stress, the Mohr-Coulomb failure criterion and hydraulic radius was discussed. Excess shear stress will not be used when evaluating remnants in this study.

In the next chapter, the selection of remnants for case study analysis, and the modelling methodology, will be discussed. The seismic history associated with the remnants will be considered, with emphases being placed on the number of events that were recorded for different local magnitudes, and on the diurnal distributions of these events.

6. Selection of Remnants and Case Studies

In Chapter 5 the theory on average pillar stress, energy release rate, excess shear stress, hydraulic radius and the Mohr-Coulomb failure criterion was discussed.

This chapter deals with the selection of remnants for case study analysis. The modelling methodology to evaluate these remnants will be discussed. The seismic history associated with the remnants will be considered, with emphases being placed on the number of seismic events that were recorded for different local magnitudes, and on the diurnal distributions of these seismic events.

6.1. Remnant Selection

For the case studies, remnants with ample seismic data, with relatively good locations at these remnants were required. This would enable the author to evaluate the diurnal distribution for different local magnitudes for these remnant case studies. Only remnants with reported seismic damage were used for the study. Ten remnants in the Free State region were selected. This would enable the author to determine if there was any trend or correlation when using the evaluation criteria discussed in Chapter 5.

The remnants mined on Bambanani Mine and Harmony 2 Shaft, ranging in depths between 1500m and 3200m, were selected as it was found that these remnants were most problematic and had adequate seismic event data available.

On Harmony 2 Shaft, the remnants being mined can be classified as Type “D” and Type “A” as discussed in Chapter 3 Section 3.4. Figure 6.1 indicates the location of these remnants on Harmony 2 Shaft.

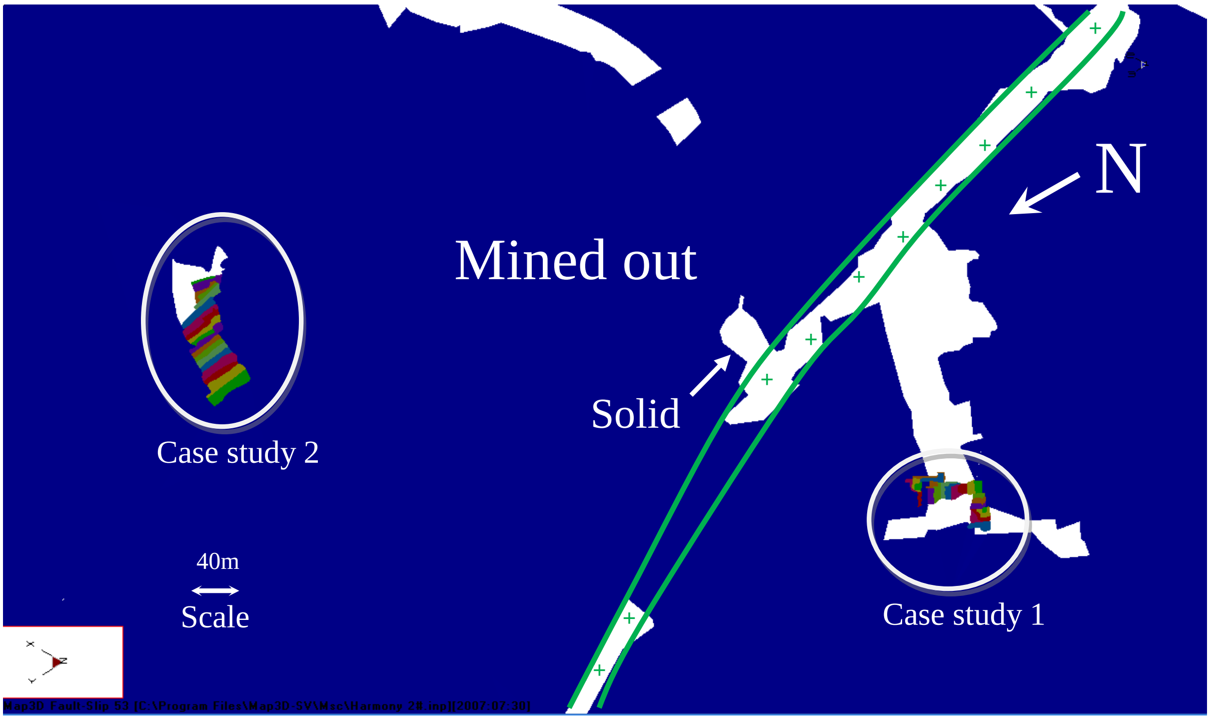


Figure 6.1 - Plan view of remnant case studies on Harmony 2 Shaft.

Remnants on Bambanani Mine can be classified as Type “A”, “B” and “C” as discussed in Chapter 3 Section 3.4. Figure 6.2 and Figure 6.3 indicate the locations of these remnants on Bambanani Mine.

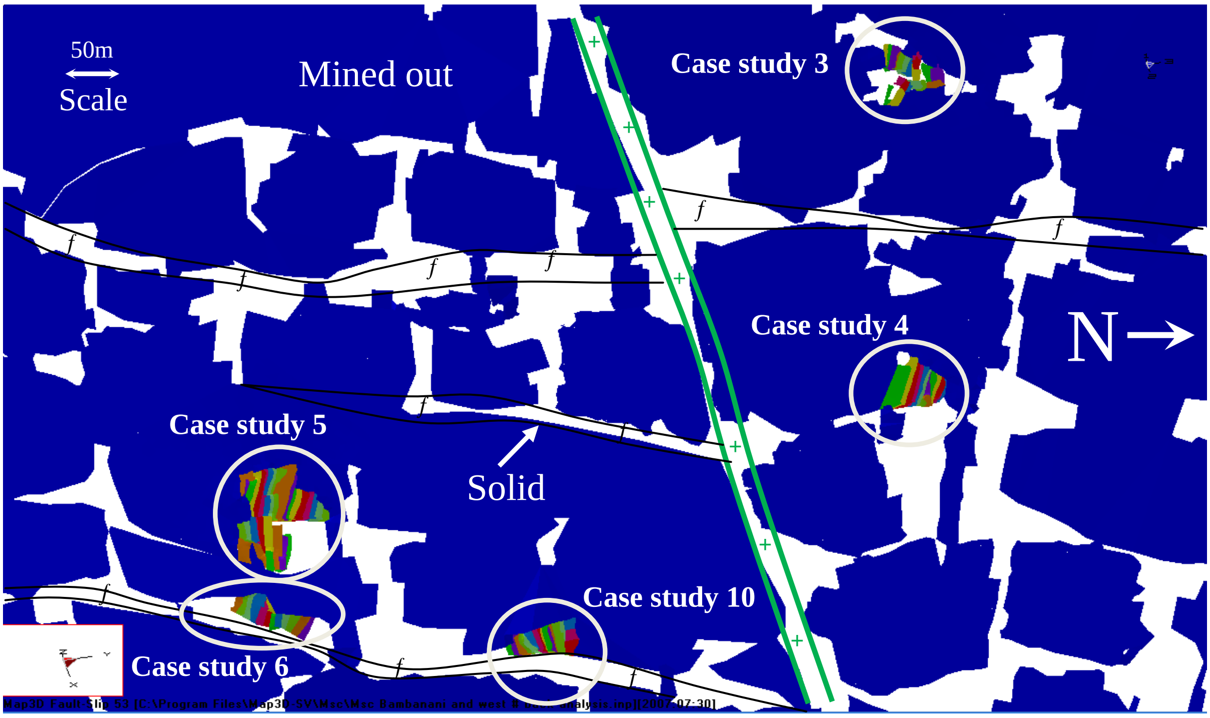


Figure 6.2 - Plan view of remnant case studies situated north of the shaft pillar on Bambanani Mine

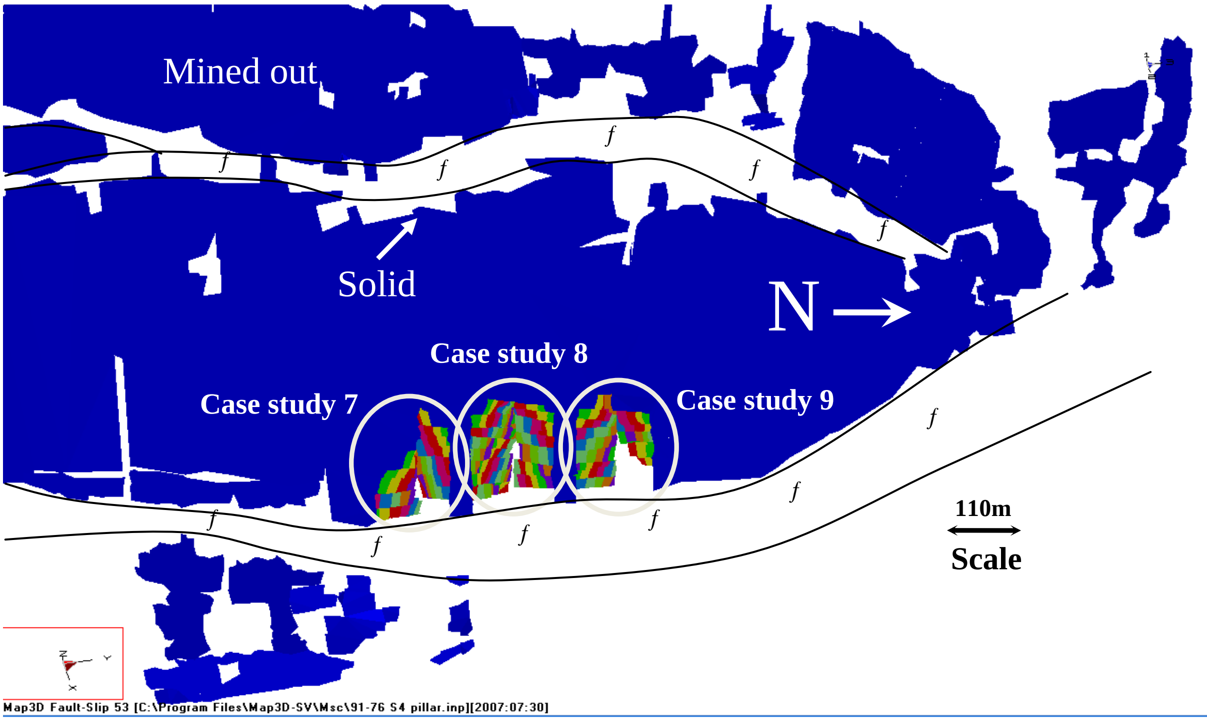


Figure 6.3 - Plan view of remnant case studies situated east of the shaft pillar on Bambanani Mine

6.2. Modelling Methodology

Numerical modelling is based on physical systems that are translated into a series of mathematical expressions. When the numerical model was constructed, Occam's Razor was applied, meaning the elimination of all unnecessary information relating to the problem that was analysed.[1]

6.2.1. Modelling Program Used

To model the remnants, a numerical model is required that will be able to model flat tabular reefs and give results for average pillar stress and energy release rate, and calculate the σ_1 and σ_3 values for given coordinates (x, y and z) at multiple mining steps in three dimensions. For the numerical modelling of the case studies MAP3D-SV will be used. MAP3D-SV is an elastic, three-dimensional, boundary element rock stability analysis package. The program is used to construct models, analyse and display displacements (m), strains, stresses (MPa), energy release rate (MN/m), excess shear stress (MPa) and strength factors.

6.2.2. Input Parameters for MAP3D

The rock mass in the numerical model is assumed to be homogeneous and isotropic to simplify numerical modelling.[3] MAP3D-SV was used to model the mining of the remnants and to determine average pillar stress, energy release rate and provide the stress values that are inputs into the Mohr-Coulomb failure criterion.

The results can be affected if the input parameters used are incorrect. To determine the average pillar stress (MPa) and energy release rates (MJ/m^2), the Young's Modulus (MPa), Poisson's ratio and density (kg/m^3) of the rock mass are required. Note that in MAP3D-SV energy release rate is expressed as MN/m and not MJ/m^2. In an attempt to be consistent energy release rate will be expressed in MJ/m^2.

J = Nm

$MJ/m^2 = MNm/m^2 = MN/m$

The following input parameters were used for MAP3D-SV: [58]

Young's modulus	: 70000 MPa
Poisson's ratio	: 0.2
Density	: 2700 kg/m3
k-ratio	: 0.5

6.3. Remnant Case Studies

Ten remnants in the Free State region were selected as previously mentioned in Chapter 6 Section 6.1. In each case study a brief description of each remnant was given.

6.3.1. Case Study 1

The remnant in case study 1 is shown in the plan in Figure 6.4. The orebody strikes north-south and dips 10º to the west. The area of the remnant measured some 20066m^2. This remnant can be classified as a Type "A" remnant as per Chapter 3 Section 3.4 and was situated some 1560m below surface and approximately 400m to the west of the Harmony 2 Shaft. The remnant was created in 1985 following mining of a 7-panel longwall towards the north. The panels stopped approximately 40m from a previously stopped longwall mined from the 25-11 No. 3 raise line. The average dimensions of the remnant were approximately 260m on dip and 75m on strike. Several minor faults intersect the remnant as shown in Figure 6.4.[57]

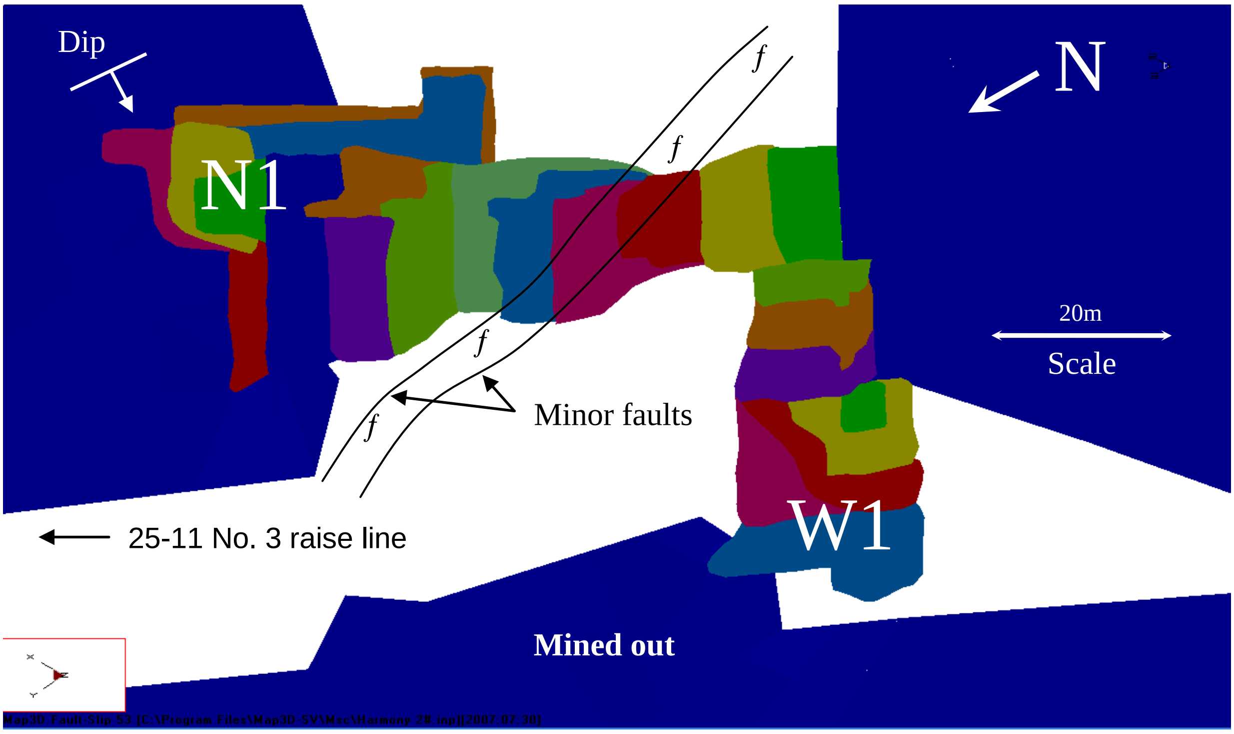


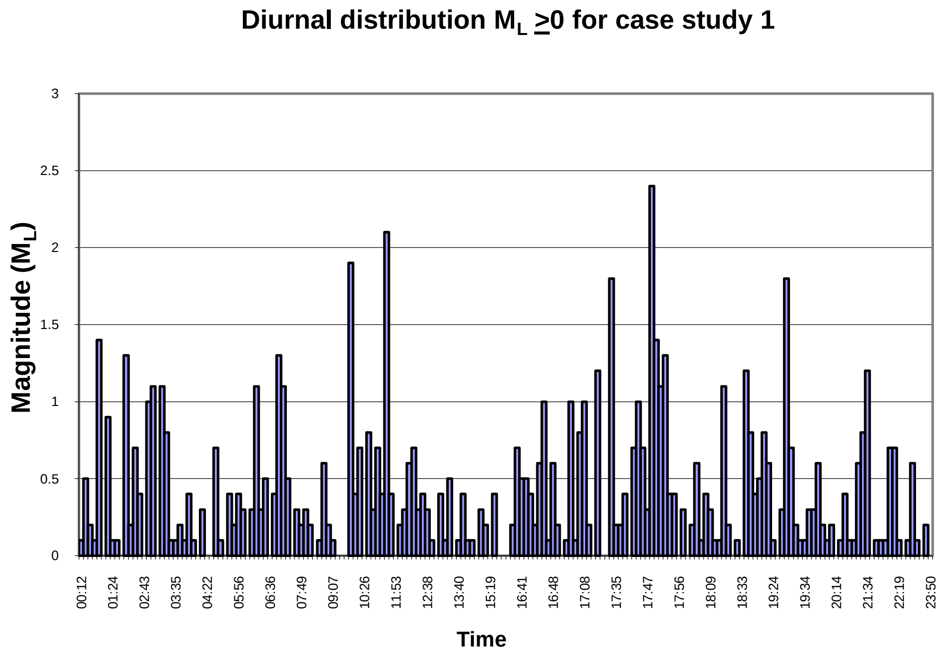
Figure 6.4 - Plan view of case study 1.

Seismic History

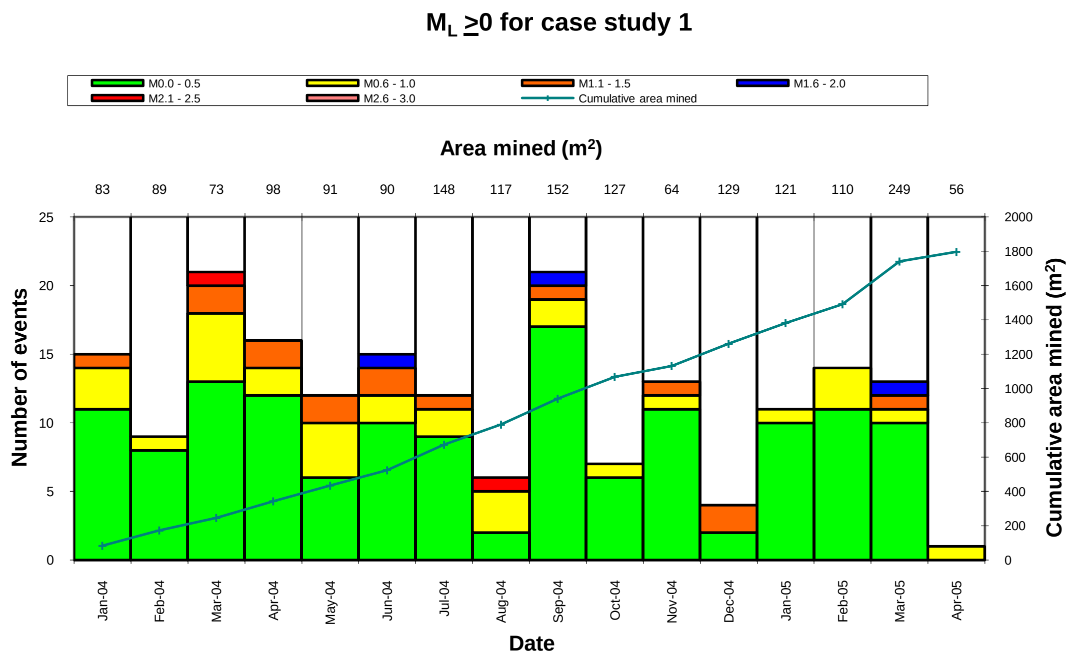
Extraction of the remnant in case study 1 commenced in January 2004 and mining of this remnant ceased in April 2005. The diurnal distribution of seismic events for the time period of mining this remnant with a local magnitude, $M_L \geq 0$ indicated that seismic events with a local magnitude, $M_L \geq 1.5$ occur randomly during the day, as shown in Graph 6.1. In Graph 6.2 the number of seismic events recorded from January 2004 to April 2005 with a local magnitude, $M_L \geq 0$ is shown. A total of 190 events were recorded as shown in Table 6.1 during the time period of mining.

M_L range	No. of events
0.0 – 0.4	138
0.5 – 0.9	32
1.0 – 1.4	15
1.5 – 1.9	3
2.0- 2.4	2

Table 6.1 - Summary of number of events for case study 1.



Graph 6.1 - Diurnal distribution of seismic events for case study 1 during the time of mining.



Graph 6.2 - Seismic events recorded at case study 1 during the time of mining.

6.3.2. Case Study 2

The remnant in case study 2 is shown in the plan in Figure 6.5 and can be classed as a Type "D" remnant as per Chapter 3 Section 3.4. The orebody strikes north-south and dips 5º to the west. The area of the remnant measured some 4119m^2 and was situated some 1500m below surface, forming part of the outer rim pillar of the Harmony 2 Shaft. The panels stopped approximately 35m from a previously stopped longwall mined from the 25-N11-raise line. The average dimensions of the remnant were approximately 117m on dip and 35m on strike.

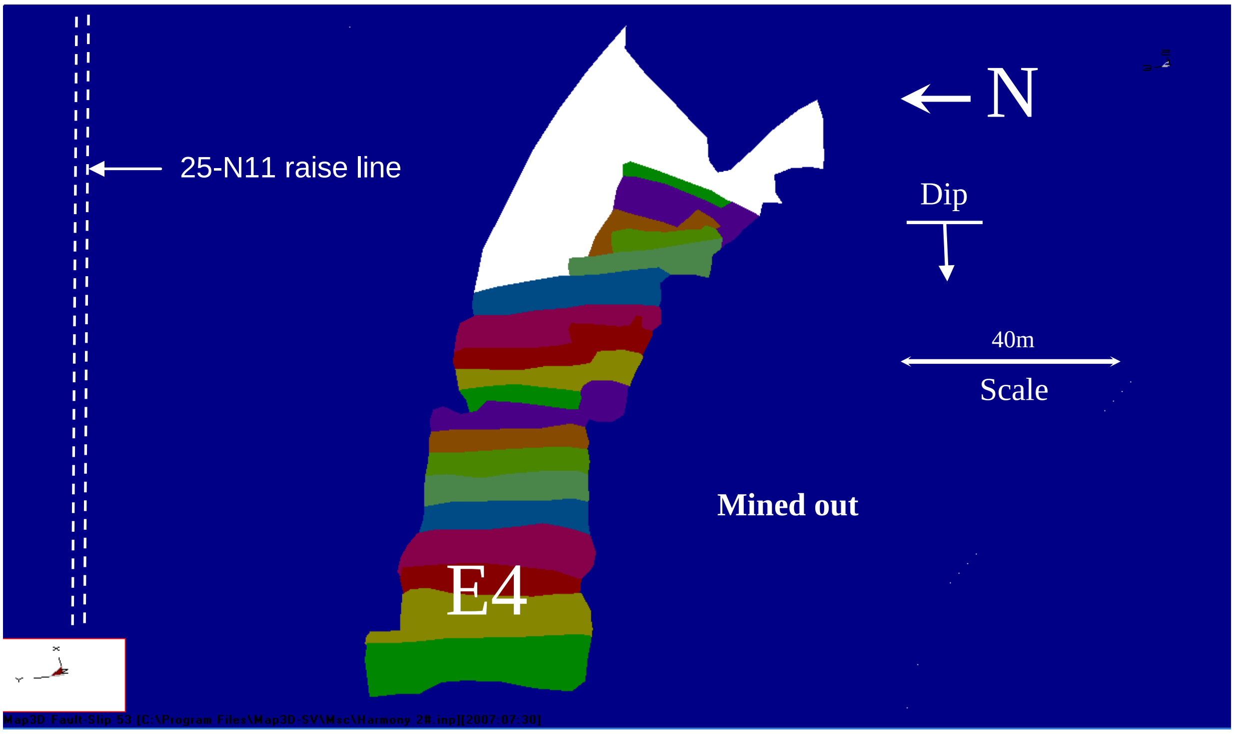


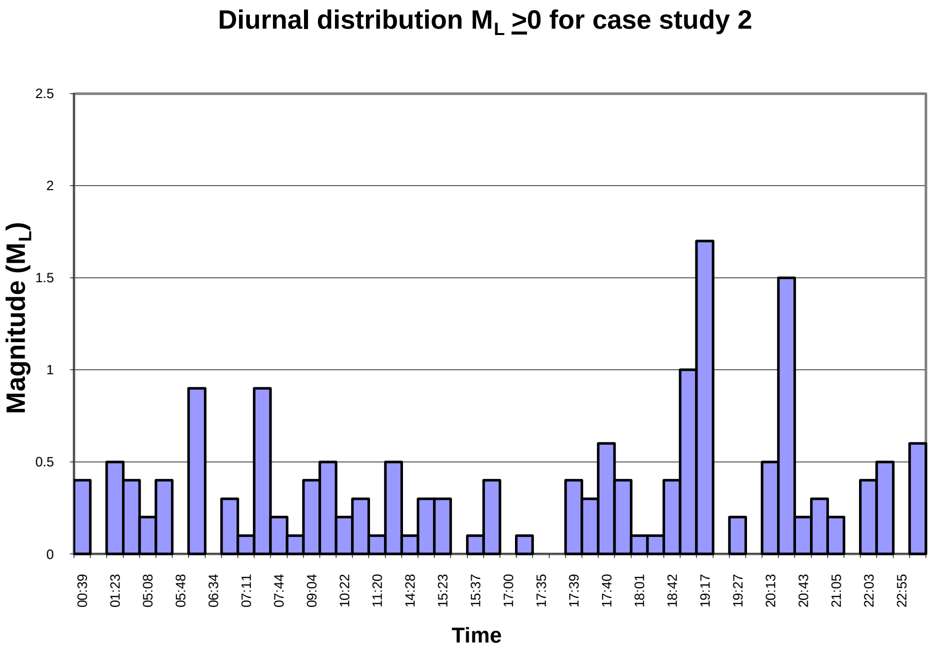
Figure 6.5 - Plan view of case study 2.

Seismic History

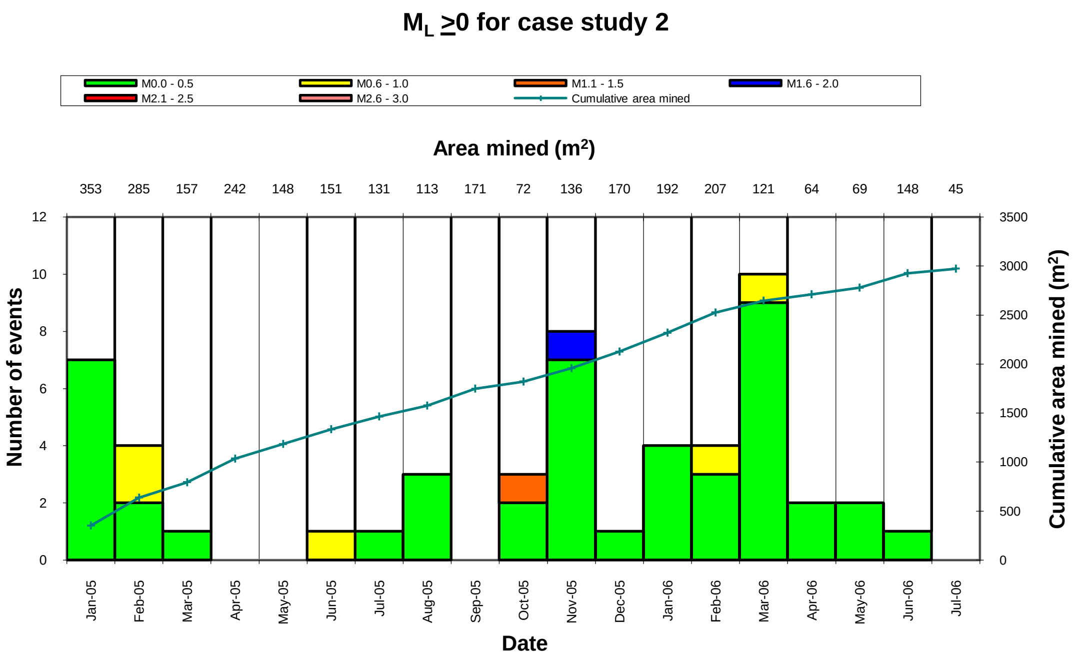
Extraction of the remnant in case study 2 commenced in January 2005 and mining of this remnant ceased in July 2006. The diurnal distribution of seismic events for the time period of mining this remnant with a local magnitude, $M_L \geq 0$ indicated that seismic events with a local magnitude, $M_L \geq 1.5$ occur during the afternoon and night shift, as shown in Graph 6.3. In Graph 6.4 the number of seismic events recorded from January 2005 to July 2006 with a local magnitude, $M_L \geq 0$ is shown. A total of 53 events were recorded as shown in Table 6.2 during the time period of mining.

M_L range	No. of events
0.0 – 0.4	45
0.5 – 0.9	5
1.0 – 1.4	1
1.5 – 1.9	2
2.0- 2.4	0

Table 6.2 - Summary of number of events for case study 2.



Graph 6.3 - Diurnal distribution of seismic events for case study 2 during the time of mining.



Graph 6.4 - Seismic events recorded at case study 2 during the time of mining.

6.3.3. Case Study 3

The remnant in case study 3 is shown in the plan in Figure 6.6. The orebody strikes north-south and dips 27º to the east. The area of the remnant measured some 3880m^2. This remnant can be classified as a Type "D" remnant as per Chapter 3 Section 3.4 and was situated some 1771m below surface and approximately 1150m to the north-west of the Bambanani Mine shaft pillar. The remnant was created in 1979 following mining done on West Shaft towards the south. The average dimensions of the remnant were approximately 65m on dip and 153m on strike and it was situated along a 5m roll fault on the east of the remnant as shown in Figure 6.6.

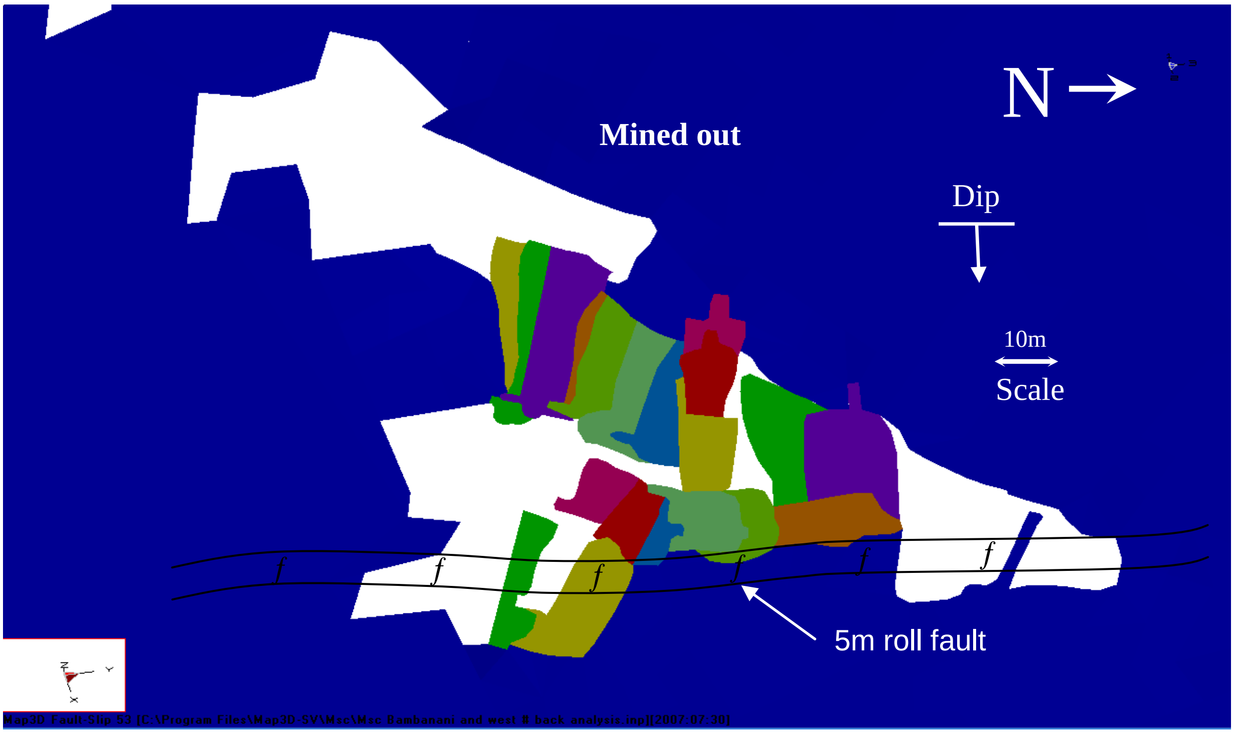


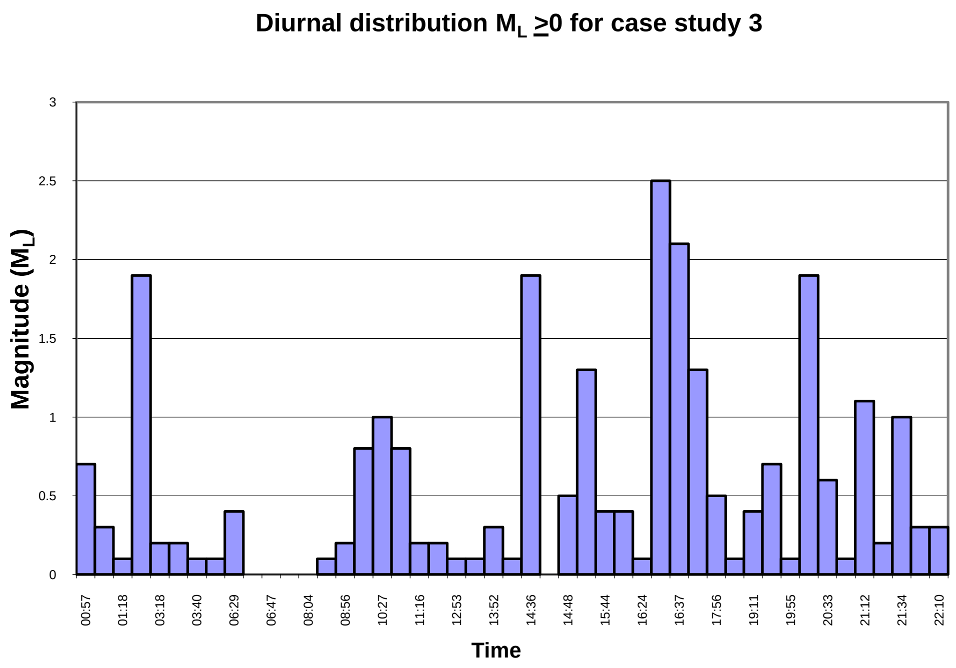
Figure 6.6 - Plan view of case study 3.

Seismic History

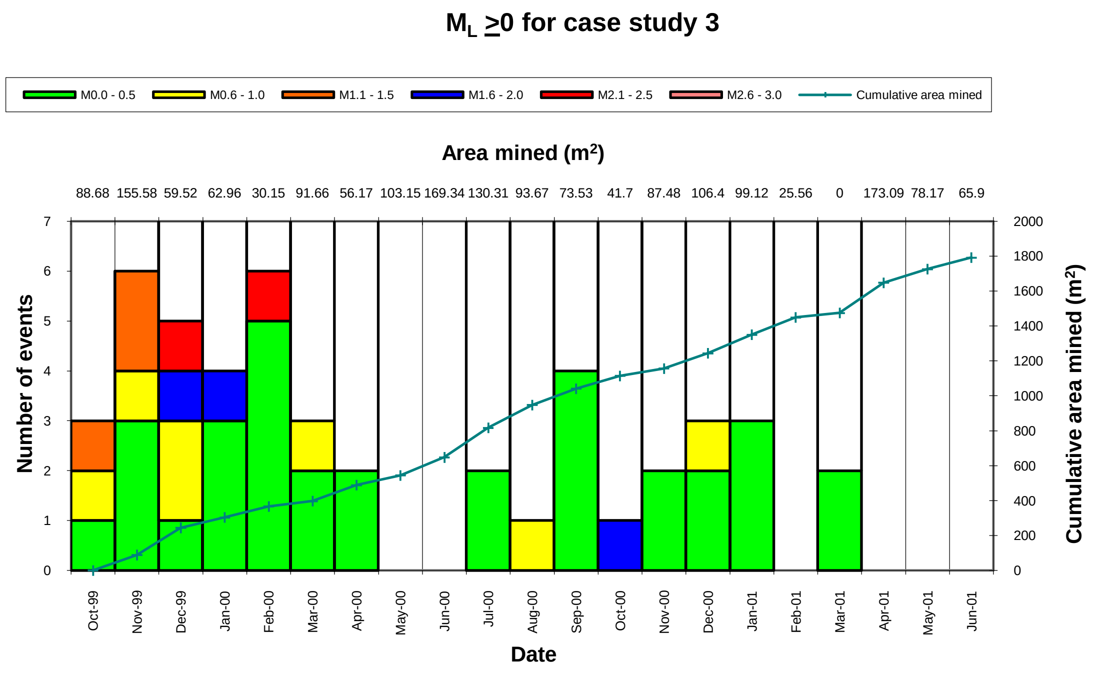
Extraction of the remnant in case study 3 commenced in October 1999 and mining of this remnant ceased in June 2001. The diurnal distribution of seismic events for the time period of mining this remnant with a local magnitude, $M_L \geq 0$ indicated that seismic events with a local magnitude, $M_L \geq 1.5$ occur randomly during the day, as shown in Graph 6.5. In Graph 6.6 the number of seismic events recorded from October 1999 to June 2001 with a local magnitude, $M_L \geq 0$ is shown. A total of 47 events were recorded as shown in Table 6.3 during the time period of mining.

M_L range	No. of events
0.0 – 0.4	32
0.5 – 0.9	7
1.0 – 1.4	3
1.5 – 1.9	3
2.0- 2.4	1
>2.4	1

Table 6.3 - Summary of number of events for case study 3.



Graph 6.5 - Diurnal distribution of seismic events for case study 3 during the time of mining.



Graph 6.6 - Seismic events recorded at case study 3 during the time of mining.

6.3.4. Case Study 4

The remnant in case study 4 is shown in the plan in Figure 6.7. The orebody strikes north-south and dips 25º to the east. The area of the remnant measured some 9166m^2. This remnant can be classified as a Type "B" remnant as per Chapter 3 Section 3.4 and was situated some 1890m below surface and approximately 1078m to the north of the Bambanani Mine shaft pillar. The remnant was created in 1984 following mining done towards the north at Bambanani Mine. The average dimensions of the remnant were approximately 169m on dip and 54m on strike.

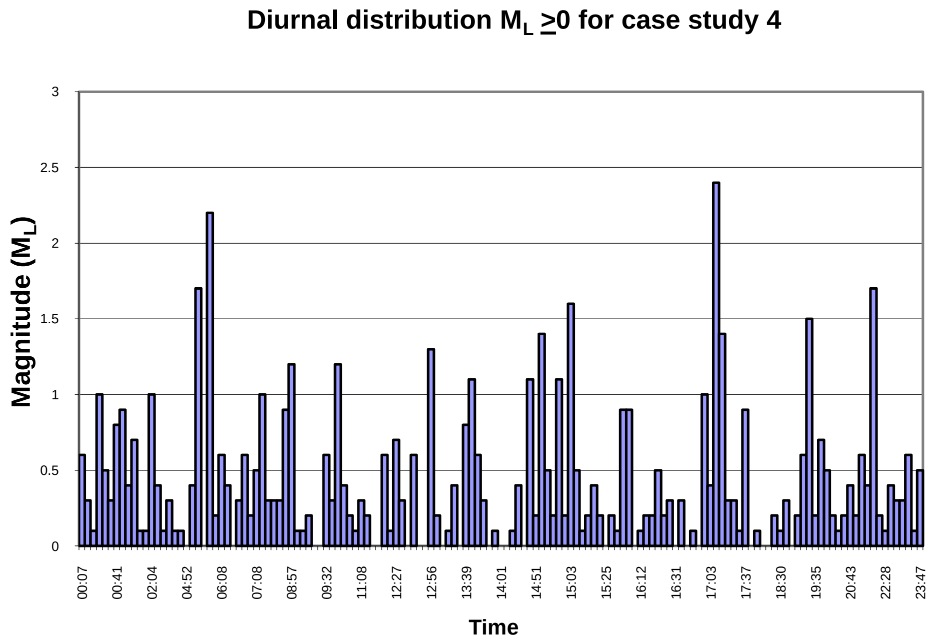
Figure 6.7 - Plan view of case study 4.

Seismic History

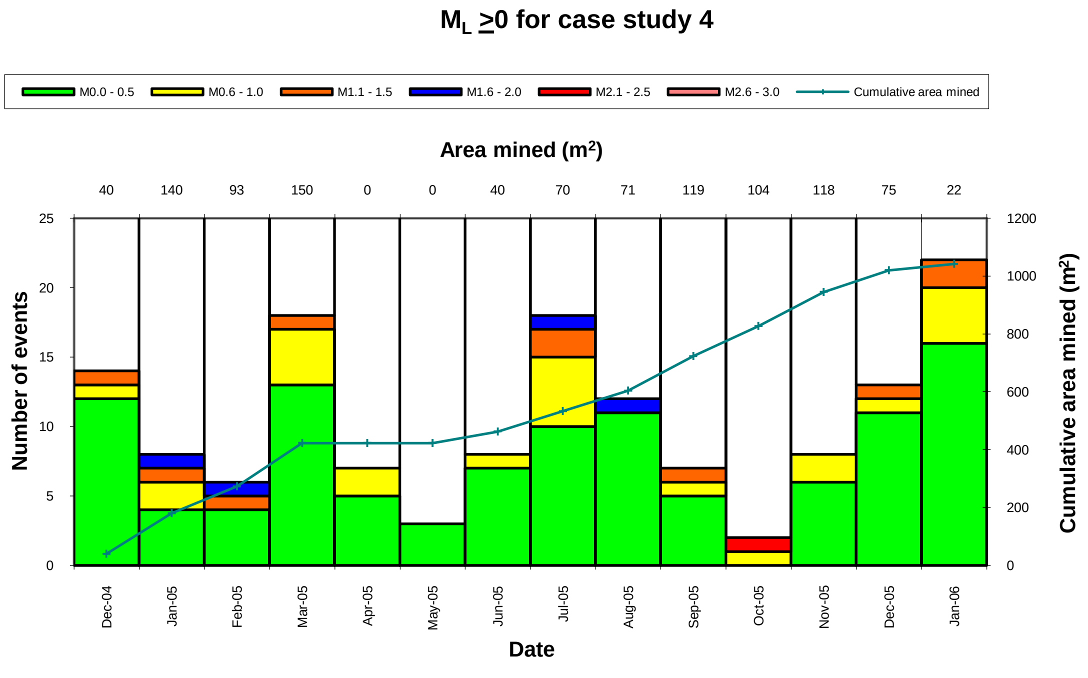
Extraction of the remnant in case study 4 commenced in December 2004 and mining of this remnant ceased in January 2006. The diurnal distribution of seismic events for the time period of mining this remnant with a local magnitude, $M_L \geq 0$ indicated that seismic events with a local magnitude, $M_L \geq 1.5$ occur randomly during the day, as shown in Graph 6.7. In Graph 6.8 the number of seismic events recorded from December 2004 to January 2006 with a local magnitude, $M_L \geq 0$ is shown. A total of 147 events were recorded as shown in Table 6.4 during the time period of mining.

M_L range	No. of events
0.0 – 0.4	107
0.5 – 0.9	24
1.0 – 1.4	10
1.5 – 1.9	4
2.0- 2.4	2

Table 6.4 - Summary of number of events for case study 4.



Graph 6.7 - Diurnal distribution of seismic events for case study 4 during the time of mining.



Graph 6.8 - Seismic events recorded at case study 4 during the time of mining.

6.3.5. Case Study 5

The remnant in case study 5 is shown in the plan in Figure 6.8. The orebody strikes north-south and dips 25º to the east. The area of the remnant measured some 4367m^2. This remnant can be classified as a Type "A" remnant as per Chapter 3 Section 3.4 and was situated some 1980m below surface and approximately 390m to the north of the Bambanani Mine shaft pillar. The remnant was created in 1986 following mining done towards the north and south. The average dimensions of the remnant were approximately 40m on dip and 132m on strike. This remnant was situated along a 25m normal fault as shown in Figure 6.8.

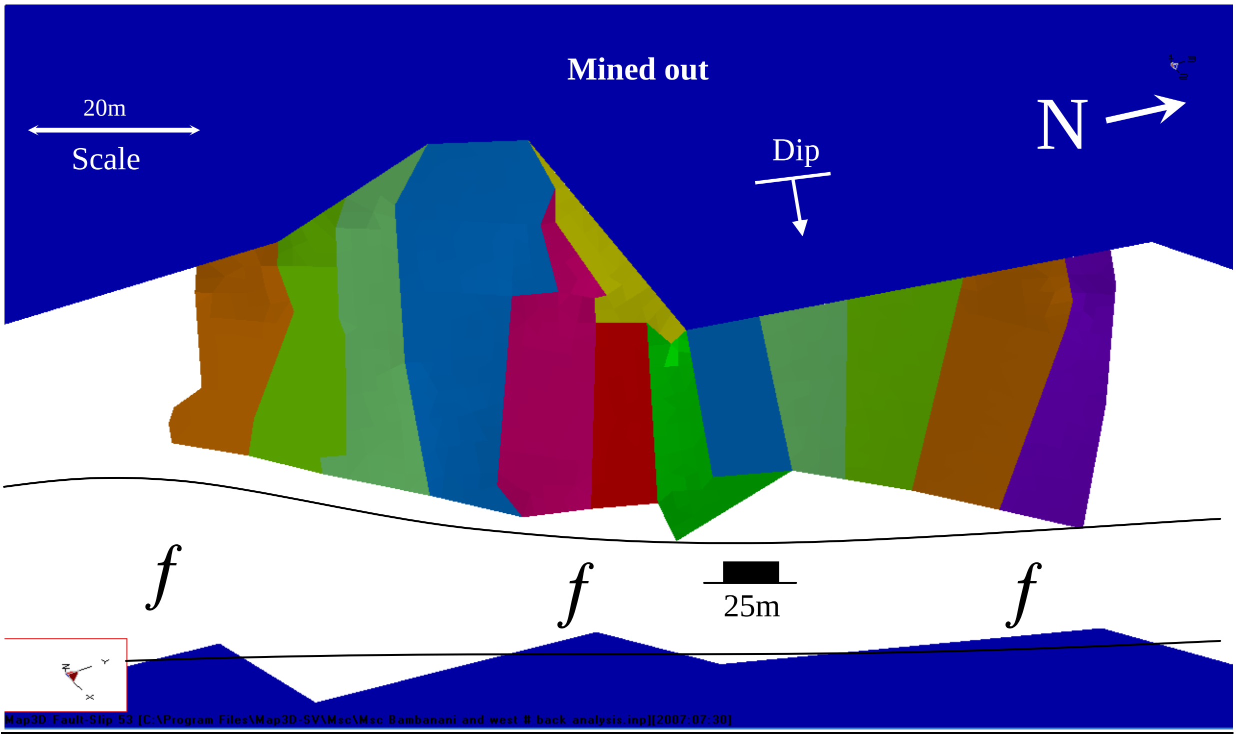


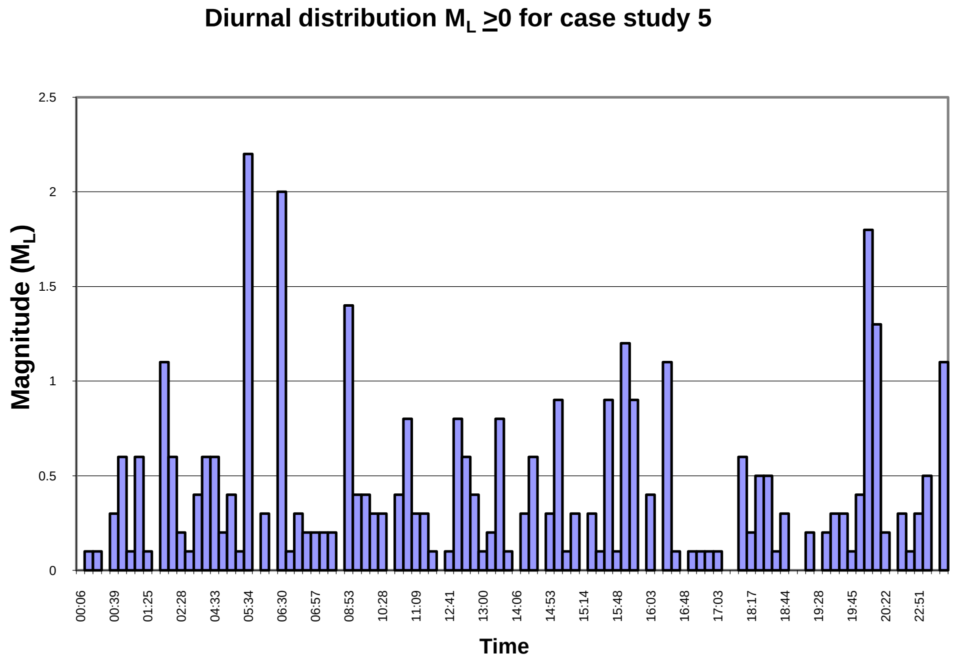
Figure 6.8 - Plan view of case study 5.

<u>Seismic History</u>

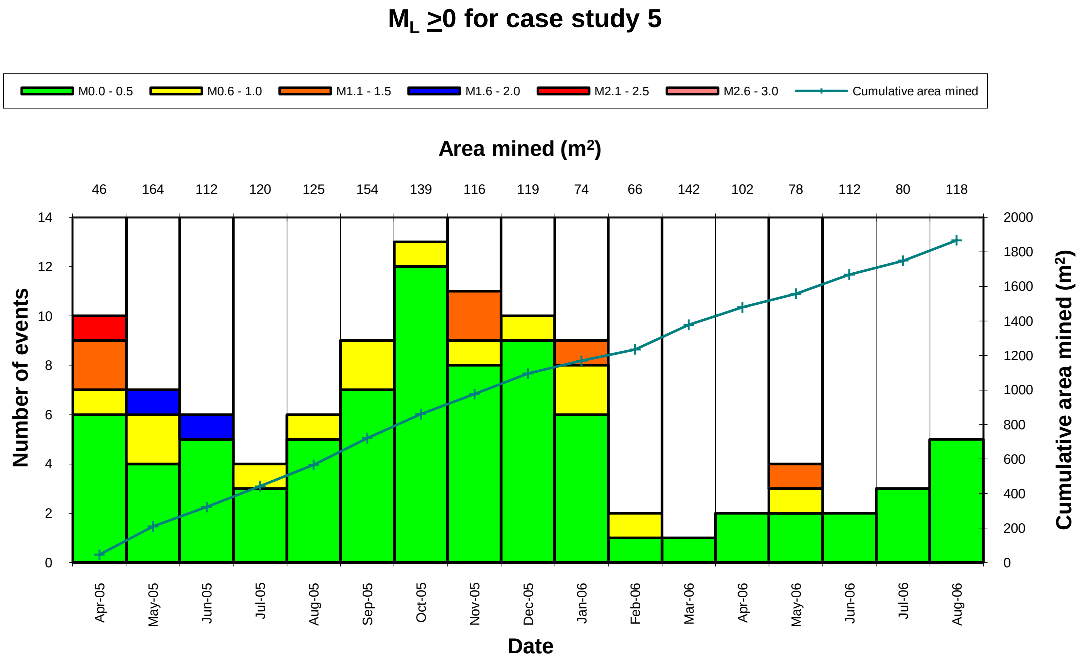
Extraction of the remnant in case study 5 commenced in April 2005 and mining of this remnant ceased in August 2006. The diurnal distribution of seismic events for the time period of mining this remnant with a local magnitude, $M_L \geq 0$ indicated that seismic events with a local magnitude, $M_L \geq 1.5$ occur during the morning and night shift, as shown in Graph 6.9. In Graph 6.10 the number of seismic events recorded from April 2005 to August 2006 with a local magnitude, $M_L \geq 0$ is shown. A total of 104 events were recorded as shown in Table 6.5 during the time period of mining.

M_L range	No. of events
0.0 – 0.4	81
0.5 – 0.9	14
1.0 – 1.4	6
1.5 – 1.9	2
2.0- 2.4	1

Table 6.5 - Summary of number of events for case study 5.



Graph 6.9 - Diurnal distribution of seismic events for case study 5 during the time of mining.



Graph 6.10 - Seismic events recorded at case study 5 during the time of mining.

6.3.6. Case Study 6

The remnant in case study 6 is shown in the plan in Figure 6.9. The orebody strikes north-south and dips 25º to the east. The area of the remnant measured some 8756m^2. This remnant can be classified as a Type "D" remnant as per Chapter 3 Section 3.4 and was situated some 1951m below surface and approximately 412m to the north of the Bambanani Mine shaft pillar. The remnant was created in 1982 following mining done towards the north and south. The average dimensions of the remnant were approximately 120m on dip and 80m on strike.

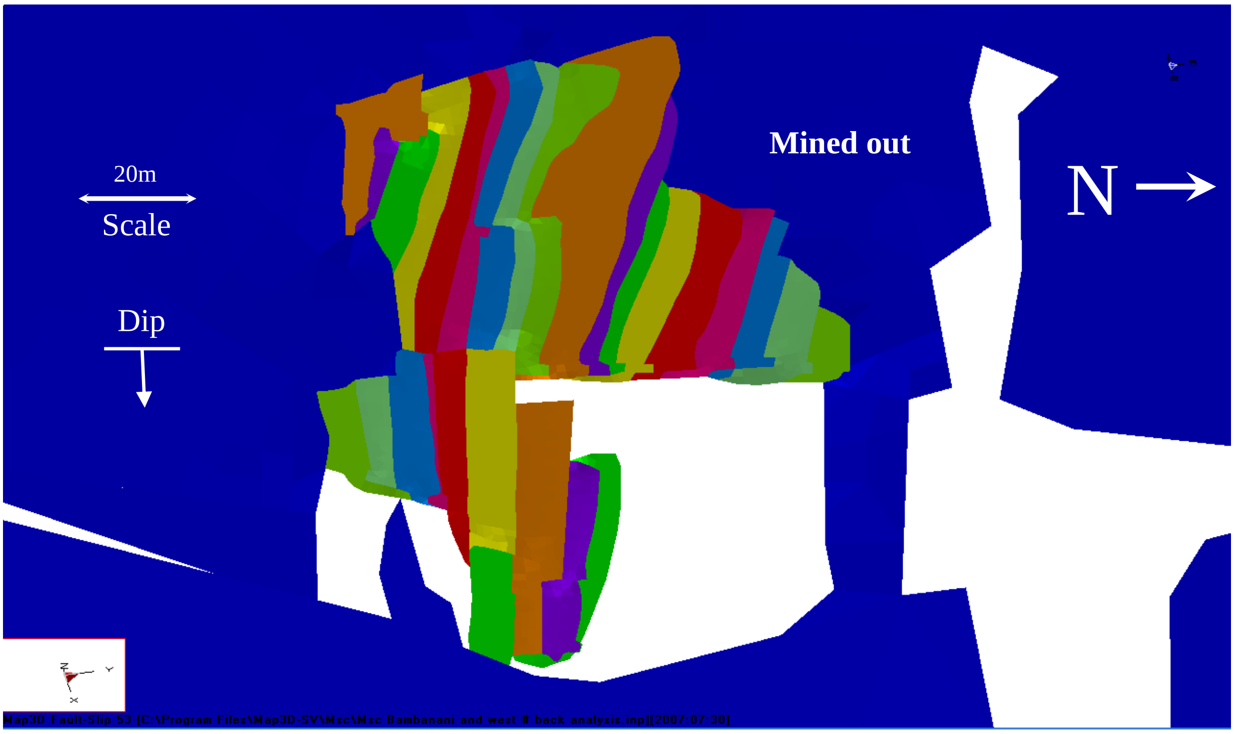


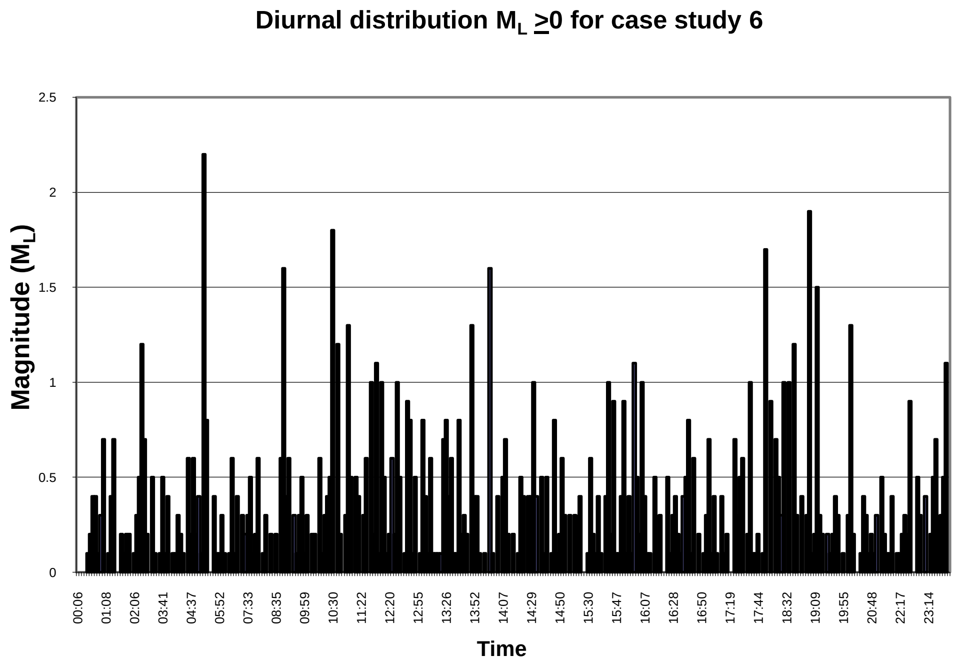
Figure 6.9 - Plan view of case study 6.

Seismic History

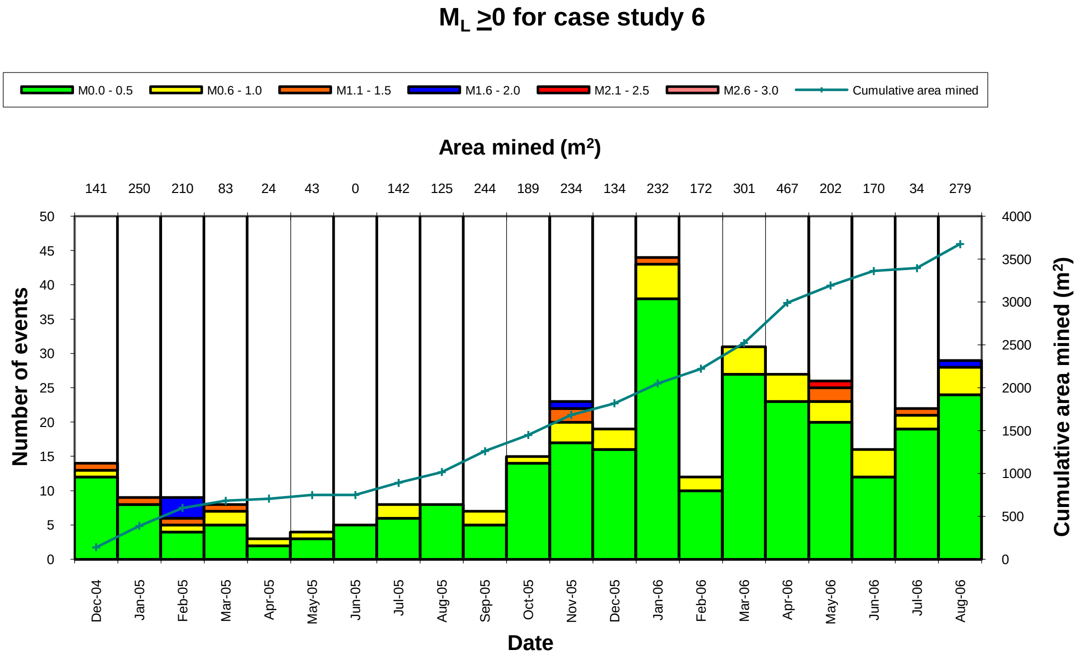
Extraction of the remnant in case study 6 commenced in December 2004. The diurnal distribution of seismic events for the time period of mining this remnant with a local magnitude, $M_L \geq 0$ indicated that seismic events with a local magnitude, $M_L \geq 1.5$ occur randomly during the day, as shown in Graph 6.11. In Graph 6.12 the number of seismic events recorded from December 2004 to August 2006 with a local magnitude, $M_L \geq 0$ is shown. A total of 340 events were recorded as shown in Table 6.6 during the time period of mining.

M_L range	No. of events
0.0 – 0.4	278
0.5 – 0.9	45
1.0 – 1.4	10
1.5 – 1.9	6
2.0- 2.4	1

Table 6.6 - Summary of number of events for case study 6.



Graph 6.11 - Diurnal distribution of seismic events for case study 6 during the time of mining.



Graph 6.12 - Seismic events recorded at case study 6 during the time of mining.

6.3.7. Case Study 7

The remnant in case study 7 is shown in the plan in Figure 6.10 and can be classified as a Type "B" remnant as per Chapter 3 Section 3.4. The orebody strikes north-south and dips 35º to the east. The area of the remnant measured some 14080m^2. This remnant was situated some 2735m below surface and approximately 1450m to the east of the Bambanani Mine shaft pillar. The remnant was created in 2001 following mining done towards the north and south. The average dimensions of the remnant were approximately 140m on dip and 110m on strike.

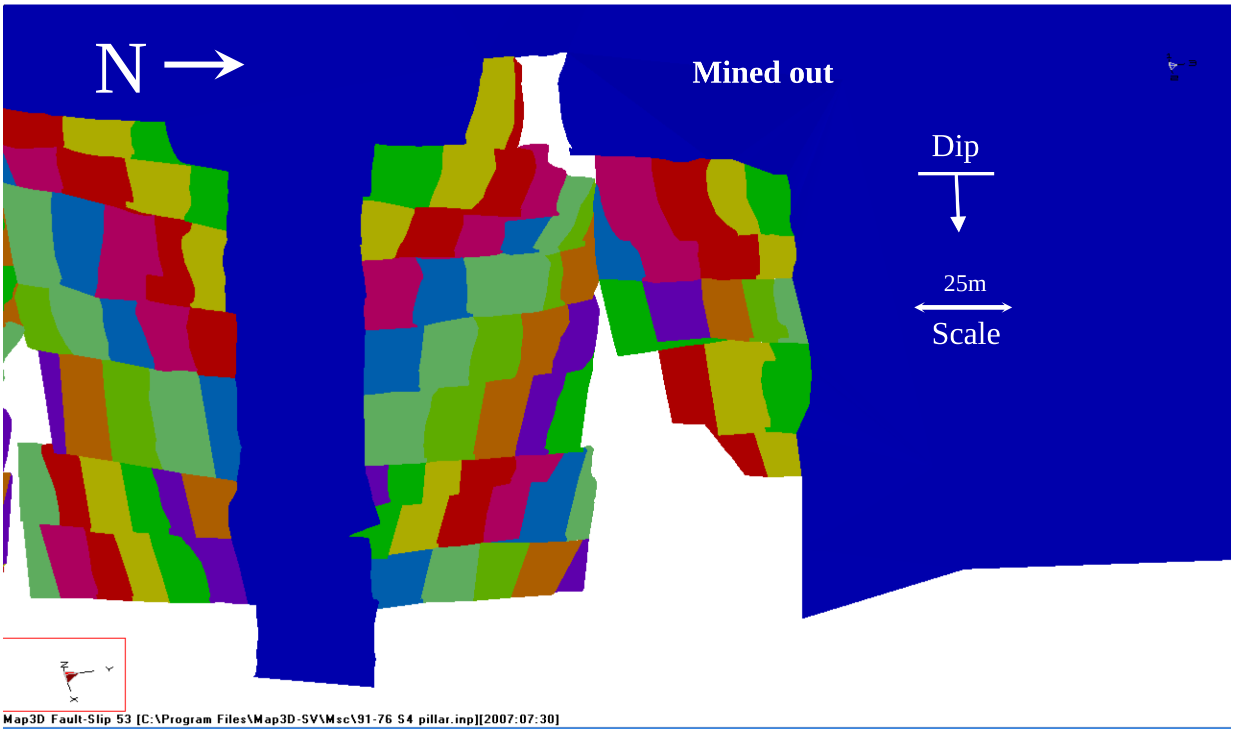


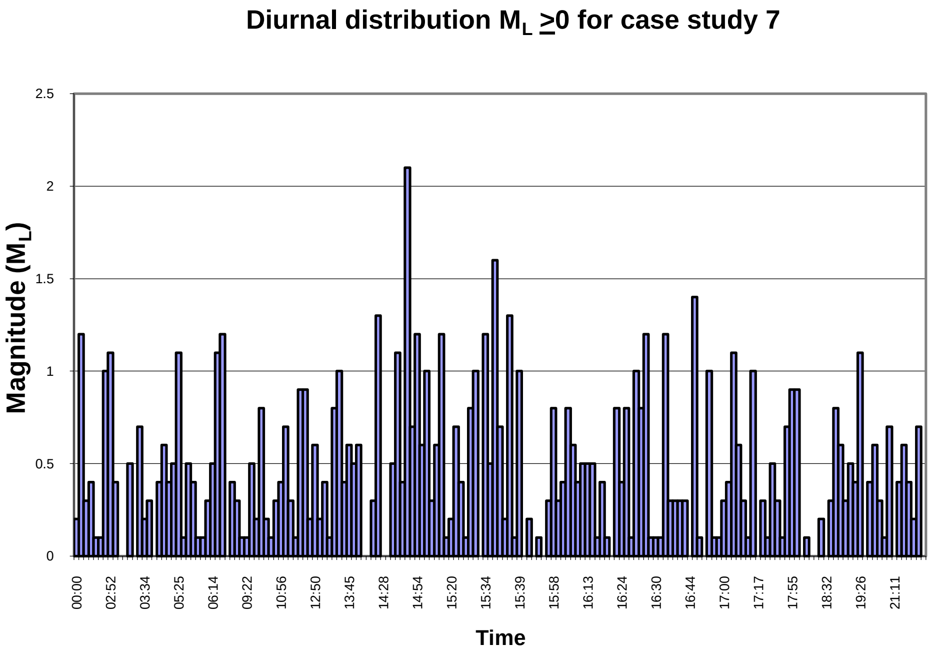
Figure 6.10 - Plan view of case study 7.

Seismic History

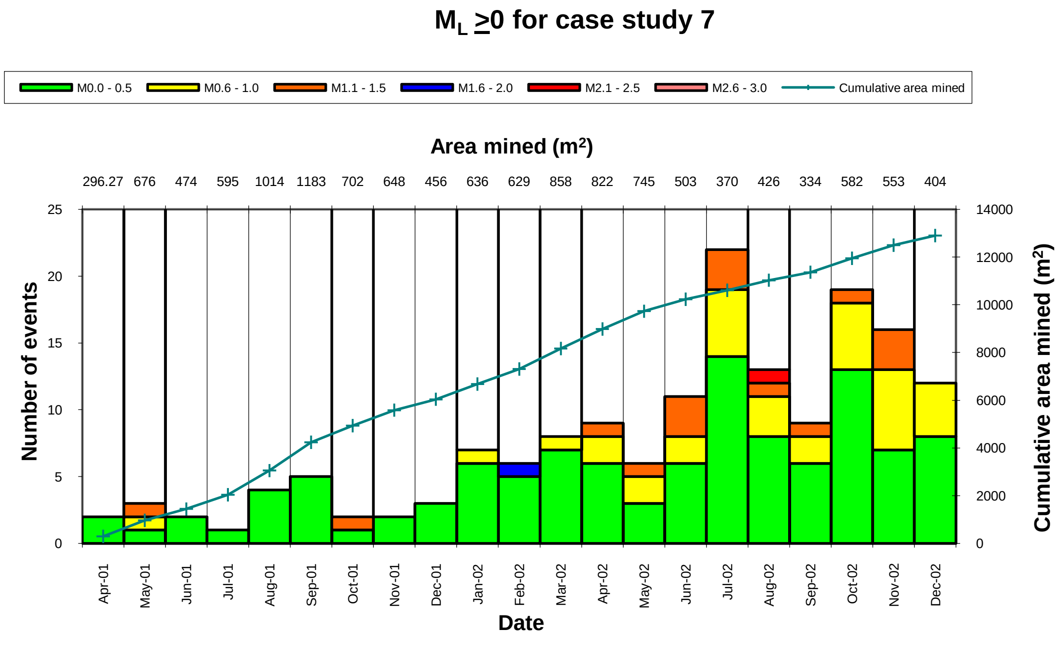
Extraction of the remnant in case study 7 commenced in April 2001. The diurnal distribution of seismic events for the time period of mining this remnant with a local magnitude, $M_L \geq 0$ indicated that seismic events with a local magnitude, $M_L \geq 1.5$ occur during the afternoon shift, as shown in Graph 6.13. In Graph 6.14 the number of seismic events recorded from April 2001 to December 2002 with a local magnitude, $M_L \geq 0$ is shown. A total of 162 events were recorded as shown in Table 6.7 during the time period of mining.

M_L range	No. of events
0.0 – 0.4	110
0.5 – 0.9	34
1.0 – 1.4	16
1.5 – 1.9	1
2.0- 2.4	1

Table 6.7 - Summary of number of events for case study 7.



Graph 6.13 - Diurnal distribution of seismic events for case study 7 during the time of mining.



Graph 6.14 - Seismic events recorded at case study 7 during the time of mining.

6.3.8. Case Study 8

The remnant in case study 8 is shown in the plan in Figure 6.11. The orebody strikes north-south and dips 35º to the east. The area of the remnant measured some 23115m². This remnant can be classified as a Type "B" remnant as per Chapter 3 Section 3.4 and was situated some 2735m below surface and approximately 1350m to the east of Bambanani Mine shaft pillar. The remnant was created in 2001 following mining done towards the north and south. The average dimensions of the remnant were approximately 175m on dip and 130m on strike.

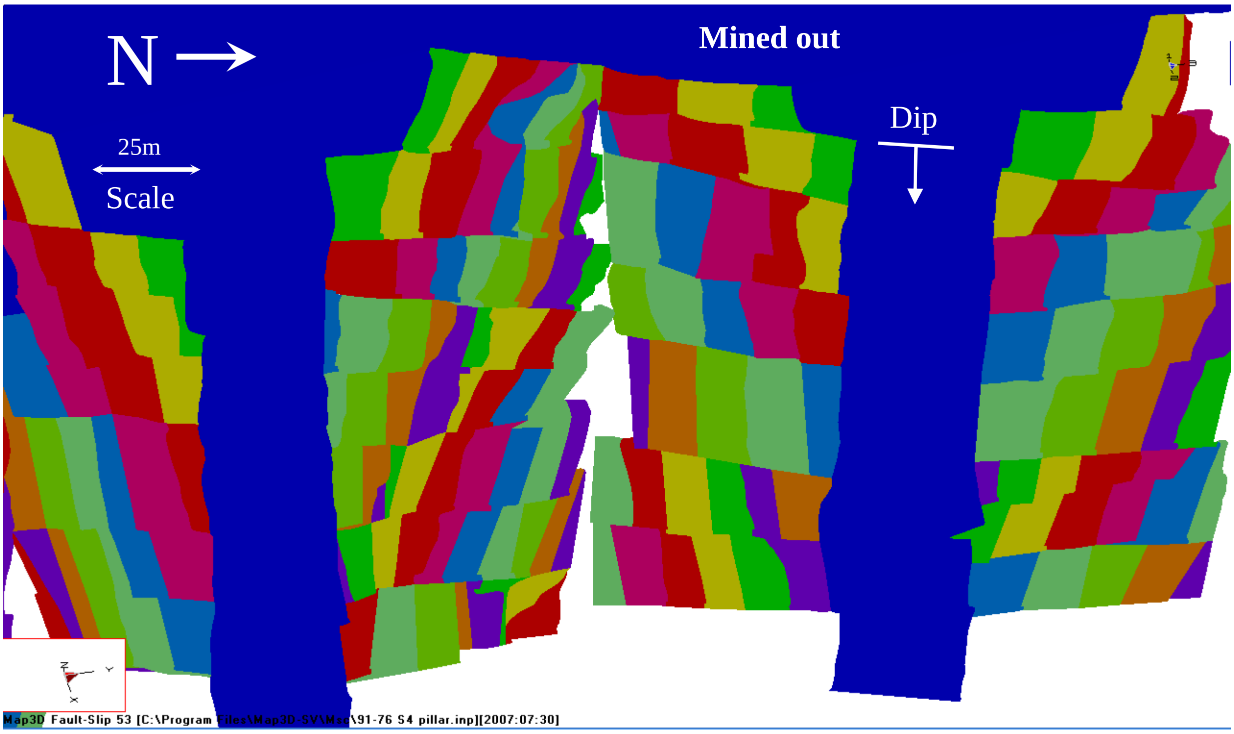


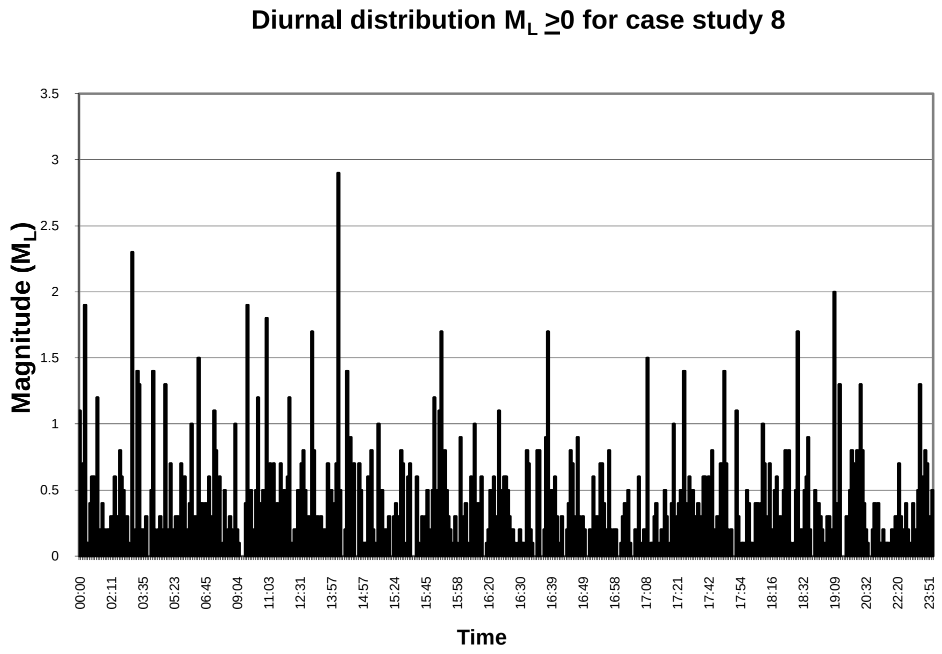
Figure 6.11 - Plan view of case study 8.

<u>Seismic History</u>

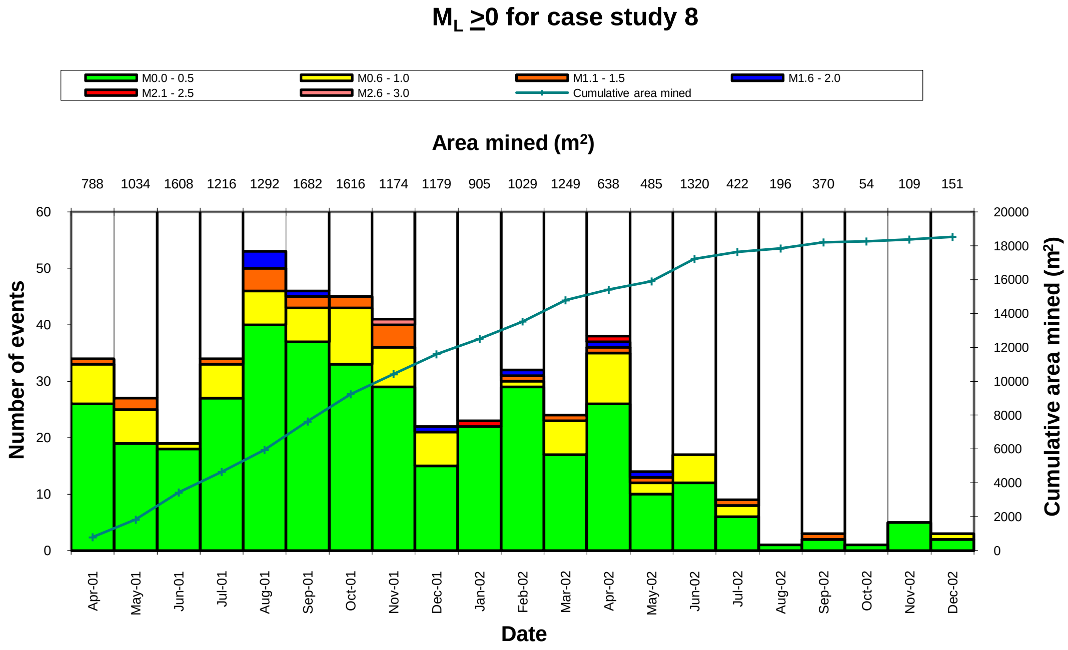
Extraction of the remnant in case study 8 commenced in April 2001 and mining of this remnant ceased in December 2002. The diurnal distribution of seismic events for the time period of mining this remnant with a local magnitude, $M_L \geq 0$ indicated that seismic events with a local magnitude, $M_L \geq 1.5$ occur randomly during the day, as shown in Graph 6.15. In Graph 6.16 the number of seismic events recorded from April 2001 to December 2002 with a local magnitude, $M_L \geq 0$ is shown. A total of 492 events were recorded as shown in Table 6.8 during the time period of mining.

M_L range	No. of events
0.0 – 0.4	377
0.5 – 0.9	81
1.0 – 1.4	22
1.5 – 1.9	9
2.0- 2.4	2
>2.4	1

Table 6.8 - Summary of number of events for case study 8.



Graph 6.15 - Diurnal distribution of seismic events for case study 8 during the time of mining.



Graph 6.16 - Seismic events recorded at case study 8 during the time of mining.

6.3.9. Case Study 9

The remnant in case study 9 is shown in the plan in Figure 6.12. The orebody strikes north-south and dips 35º to the east. The area of the remnant measured some 18721m^2. This remnant can be classified as a Type "B" remnant as per Chapter 3 Section 3.4 and was situated some 2735m below surface and approximately 1250m to the east of Bambanani Mine shaft pillar. The remnant was created in 2001 following mining done towards the north and south. The average dimensions of the remnant were approximately 180m on dip and 100m on strike.

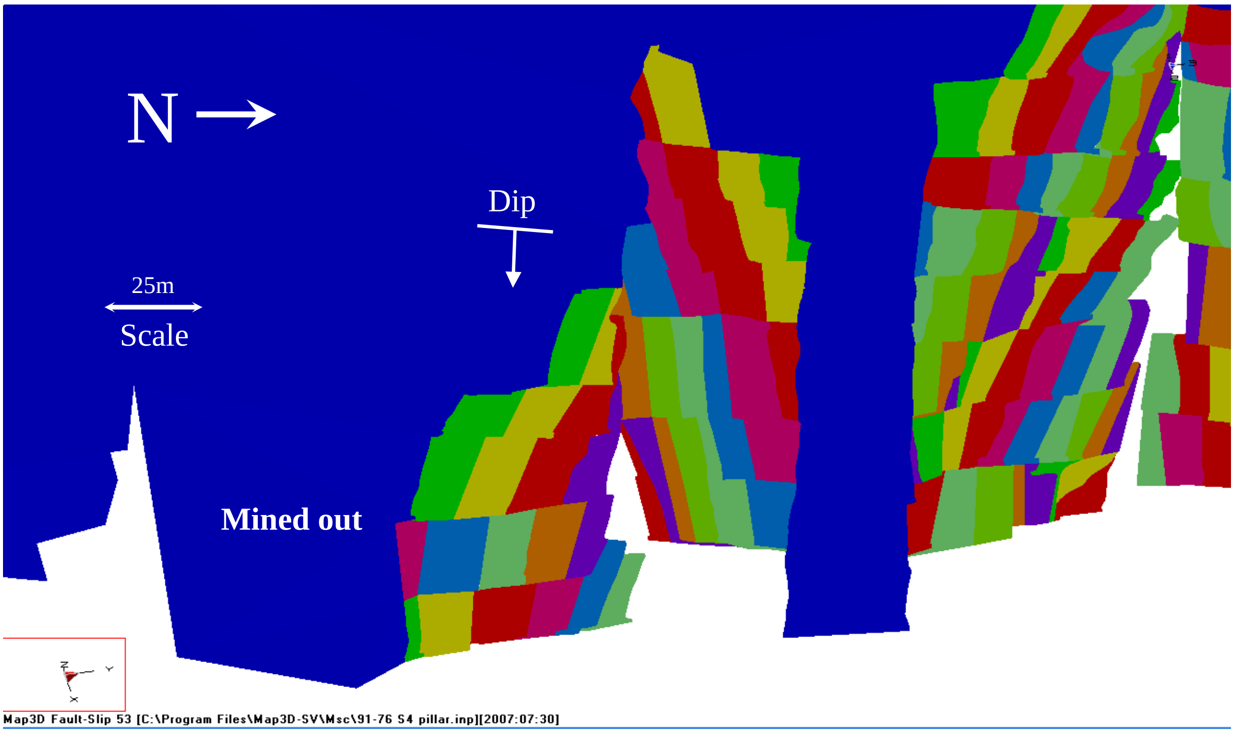


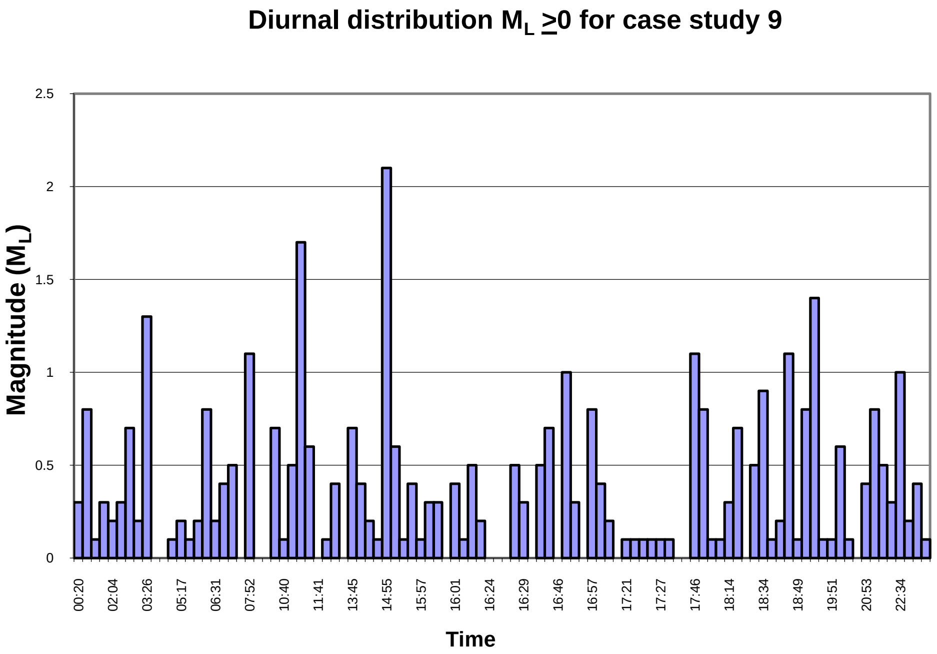
Figure 6.12 - Plan view of case study 9.

Seismic History

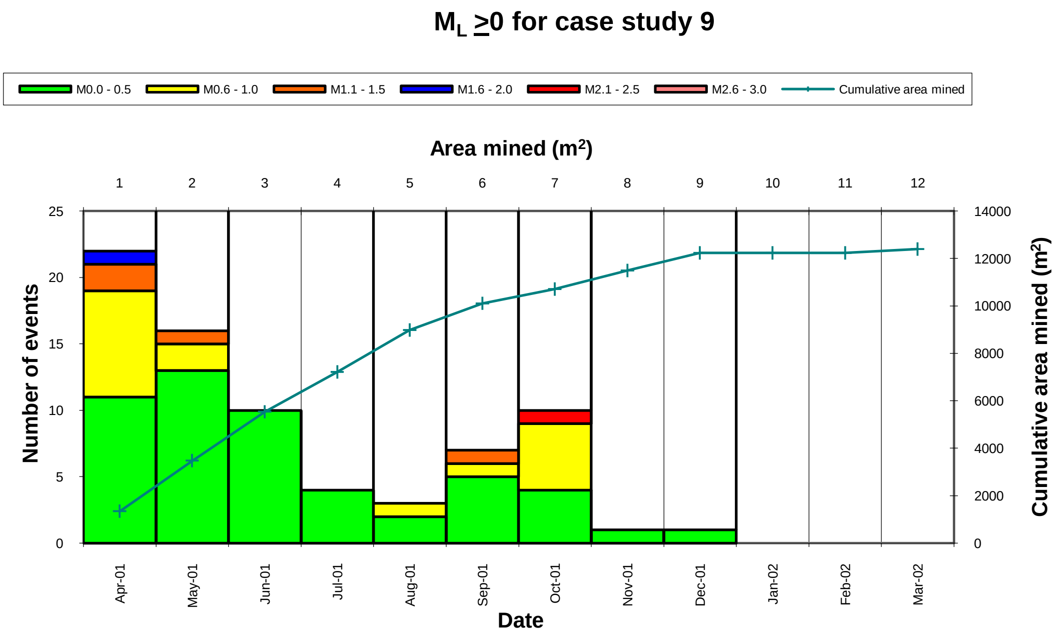
Extraction of the remnant in case study 9 commenced in April 2001 and mining of this remnant ceased in March 2002. The diurnal distribution of seismic events for the time period of mining this remnant with a local magnitude, $M_L \geq 0$ indicated that seismic events with a local magnitude, $M_L \geq 1.5$ occur during the morning and afternoon shift, as shown in Graph 6.17. In Graph 6.18 the number of seismic events recorded from April 2001 to March 2002 with a local magnitude, $M_L \geq 0$ is shown. A total of 74 events were recorded as shown in Table 6.9 during the time period of mining.

M_L range	No. of events
0.0 – 0.4	51
0.5 – 0.9	17
1.0 – 1.4	4
1.5 – 1.9	1
2.0- 2.4	1

Table 6.9 - Summary of number of events for case study 9.



Graph 6.17 - Diurnal distribution of seismic events for case study 9 during the time of mining.



Graph 6.18 - Seismic events recorded at case study 9 during the time of mining.

6.3.10. Case Study 10

The remnant in case study 10 is shown in the plan in Figure 6.13. The orebody strikes north-south and dips 24º to the east. The area of the remnant measured some 1971m². This remnant can be classified as a Type “A” remnant as per Chapter 3 Section 3.4 and was situated some 1982m below surface and approximately 700m to the north of Bambanani Mine shaft pillar. The remnant was created in 1981 following mining done towards the north and south. The average dimensions of the remnant were approximately 30m on dip and 70m on strike. This remnant was left along a 25m normal fault as shown in Figure 6.13.

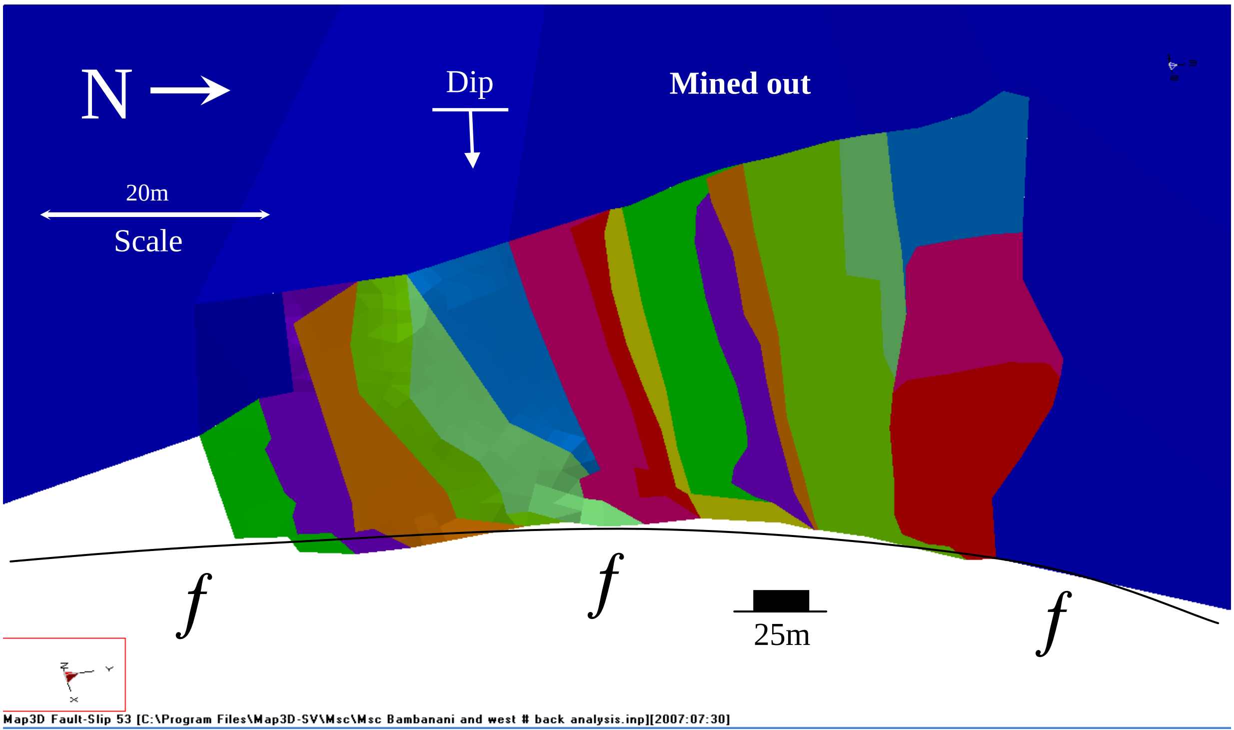


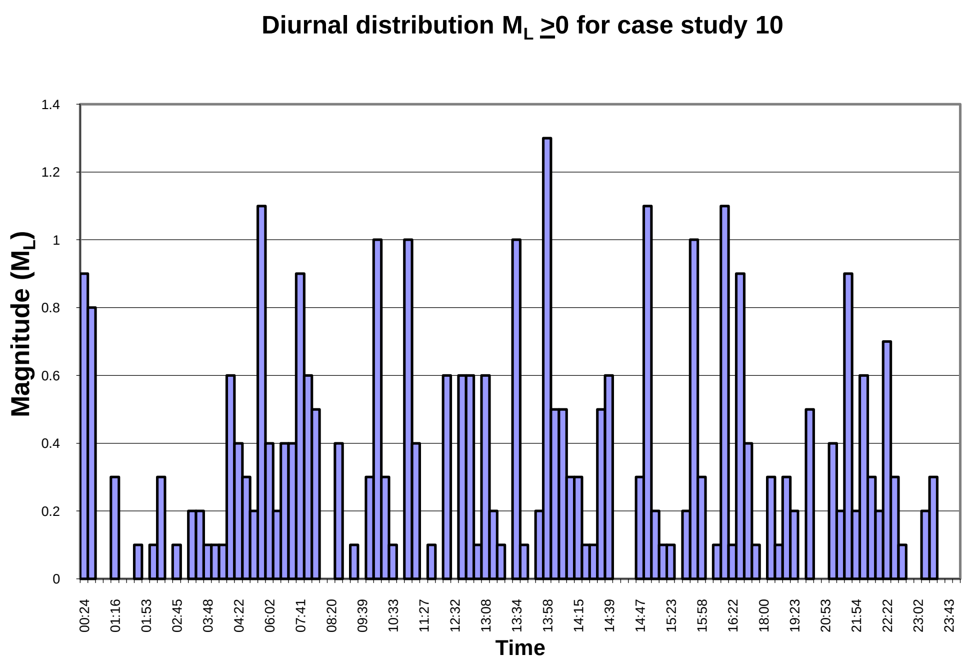
Figure 6.13 - Plan view of case study 10.

Seismic History

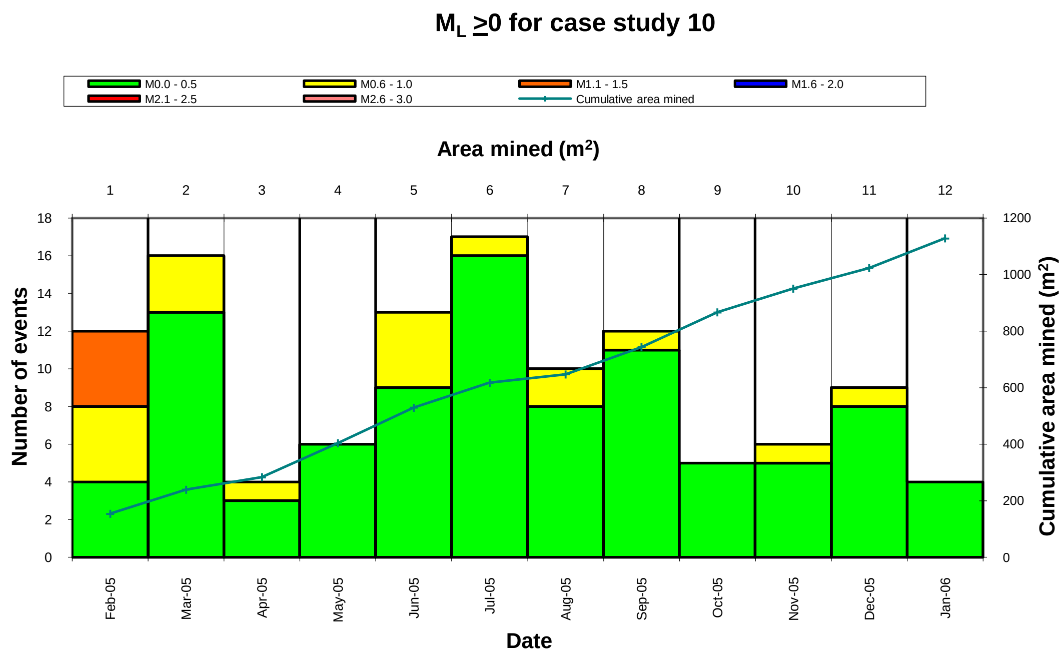
Extraction of the remnant in case study 10 commenced in February 2005 and mining of this remnant ceased in January 2006. The diurnal distribution of seismic events for the time period of mining this remnant with a local magnitude, $M_L \geq 0$ indicated that no seismic events with a local magnitude, $M_L \geq 1.5$ occurred, as shown in Graph 6.19. In Graph 6.20 the number of seismic events recorded from February 2005 to January 2006 with a local magnitude, $M_L \geq 0$ is shown. A total of 114 events were recorded as shown in Table 6.10 during the time period of mining.

M_L range	No. of events
0.0 – 0.4	92
0.5 – 0.9	18
1.0 – 1.4	4
1.5 – 1.9	0
2.0- 2.4	0

Table 6.10 - Summary of number of events for case study 10.



Graph 6.19 - Diurnal distribution of seismic events for case study 10 during the time of mining.



Graph 6.20 - Seismic events recorded at case study 10 during the time of mining.

6.4. Summary

Ten remnants in the Free State region were selected for the case studies. This would enable the author to determine whether there was any trend or correlation in the evaluation criteria discussed in Chapter 5. The seismic history and diurnal distribution of seismic events for each case study was discussed.

The next chapter will present the analysis of the results obtained from the case studies, comparing these results with those currently used in the mining industry. Based on the case study results, a new remnant evaluation criterion, The Remnant Failure Index (RFI) was developed for the evaluation of remnants in the Free State. In the next chapter the newly developed Remnant Failure Index and the application there of, will be discussed.

7. Analysis and Results

In Chapter 6 ten remnants in the Free State region were selected for the case studies. This would enable the author to determine whether there was any trend or correlation in the evaluation criteria discussed in Chapter 5. The seismic history and diurnal distribution of seismic events for each case study was discussed.

This chapter will present the analysis of the results obtained from the case studies. The results obtained will be compared to those currently being used in the mining industry. When mining remnants the potential occurrence of rockbursts is of great concern. A new remnant evaluation criterion, the Remnant Failure Index (RFI) was developed for the evaluation of remnants in the Free State, based on the case study results. This chapter will also discuss how the newly developed RFI can be applied when evaluating remnants.

7.1. Seismic History of Case Studies

As part of the evaluation process of these case studies the seismic history and diurnal distribution of these seismic events will be evaluated and discussed.

From the results obtained in Chapter 6, it was found that the diurnal distribution indicated that 39% of the seismic events with a local magnitude, $M_L \geq 1.5$ occurred during the morning shift as shown in Table 7.1. This was of concern, as production personnel were working at the stope face during this time.

Case Studies Diurnal distribution	**Day Shift (6h00 – 14h00)**	**Afternoon Shift (14h00 – 20h00)**	**Night Shift (20h00 – 6h00)**
Case study 1	2	3	-
Case study 2	-	1	1
Case study 3	1	4	-
Case study 4	2	3	1
Case study 5	2		1
Case study 6	3	4	-
Case study 7	-	2	-
Case study 8	6	6	-
Case study 9	1	1	-
Case study 10			
Total of 44 events with $M_L \geq 1.5$	17	24	3
% Distribution	39%	55%	6%

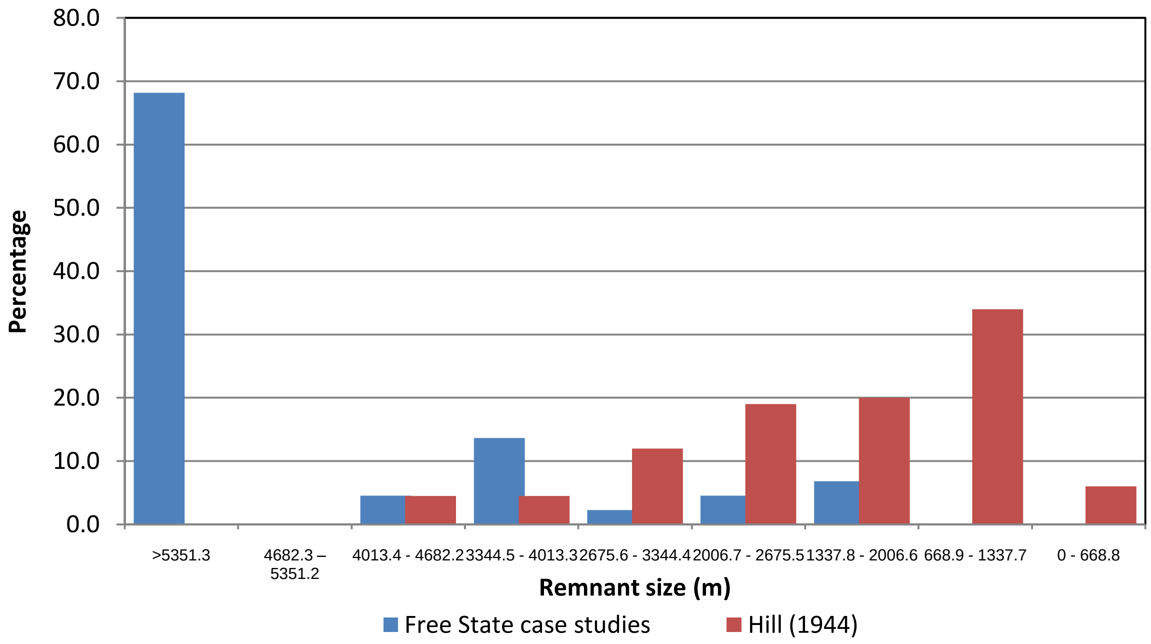
Table 7.1 - Summary of case studies showing diurnal distribution of seismic events $M_L \geq 1.5$.

In Table 7.2 and Graph 7.1 the number of events with a local magnitude, $M_L \geq 1.5$ versus the area of the remnant are shown in the same intervals as Hill [20]. It must be noted that the magnitude of events used by Hill [20] were not quoted. For the Free State it was found that damage only starts to occur in remnants when the local magnitude, $M_L \geq 1.5$ for these events. The seismic events obtained in Chapter 6 for the case studies, indicated a decrease in seismicity for events with a local magnitude, $M_L \geq 1.5$ with decreasing remnant area as shown in Table 7.2 and Graph 7.1. This contradicts the findings of Hill [20] that seismicity increases with decreasing area of the remnant.

From Table 7.2, remnants >5350m^2 are most seismically active in the Free State with a sharp drop in seismicity when smaller than this. Two possible explanations for the different behaviour for these remnants, compared to Hill [20], could be due to the geotechnical conditions such as the shale overlying the reef as discussed in Chapter 4 Section 4.2.

Size of remnant measured in square meters (m^2)	Seismic events M_L>? recorded by Hill [20]	Percentage events for various sizes of remnants	Case studies Seismic events $M_L \geq 1.5$	Percentage events for various sizes of remnants
>5351.3	0	0	30	68.2
4682.3 – 5351.2	0	0	0	0.0
4013.4 - 4682.2	6	4.5	2	4.5
3344.5 - 4013.3	6	4.5	6	13.6
2675.6 - 3344.4	16	12.0	1	2.3
2006.7 - 2675.5	25	19.0	2	4.5
1337.8 - 2006.6	27	20.0	3	6.8
668.9 - 1337.7	46	34.0	0	0.0
0 - 668.8	8	6.0	0	0.0
No. of seismic events	**134**	**100.0**	**44**	**100.0**
No. of Remnants	**36**		**10**	
Seismic events per remnant	**3.7**		**4.4**	

Table 7.2 - Number of seismic events $M_L \geq 1.5$ recorded at case studies versus Hill [20].



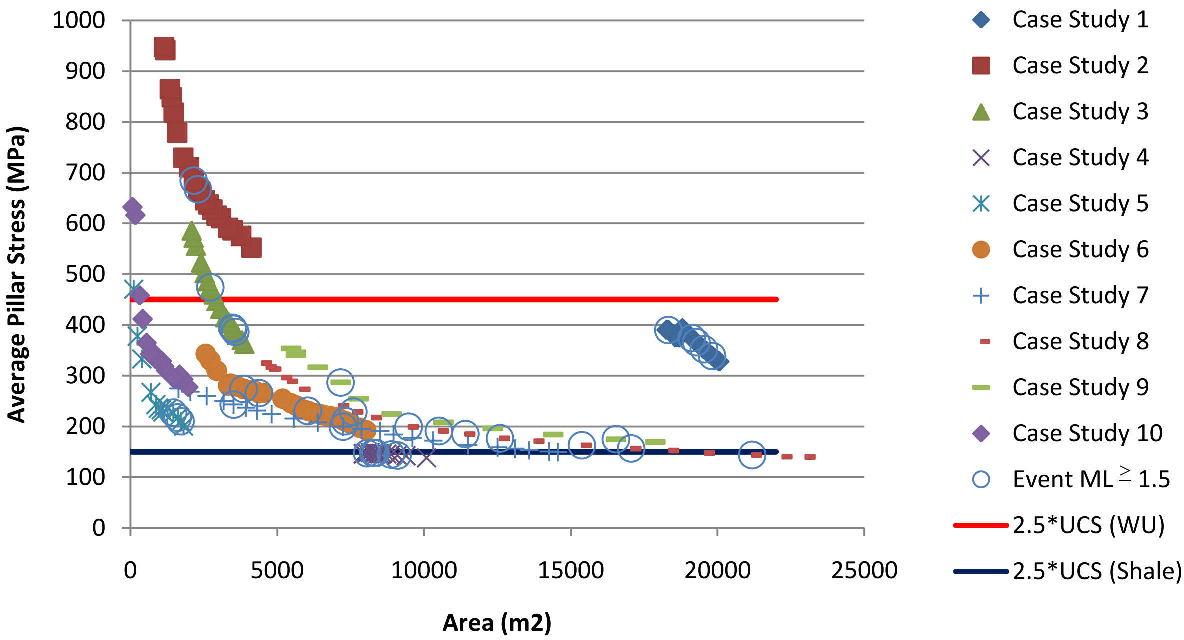
Graph 7.1 - Shows percentage events to remnant size (m^2).

7.2. Average Pillar Stress (APS)

The pillar strength criterion developed for the evaluation of pillar punching and foundation failure of stability pillars, as discussed in Section 5.1, were used to evaluate these remnants. As no punching of the foundation of these remnants was observed, the criterion for foundation failure, APS<$2.5\sigma_c$, was used to evaluate the case studies. The average pillar stress at each mining step is plotted, with decreasing remnant area, as to determine if there is any correlation between APS and area for these remnants.

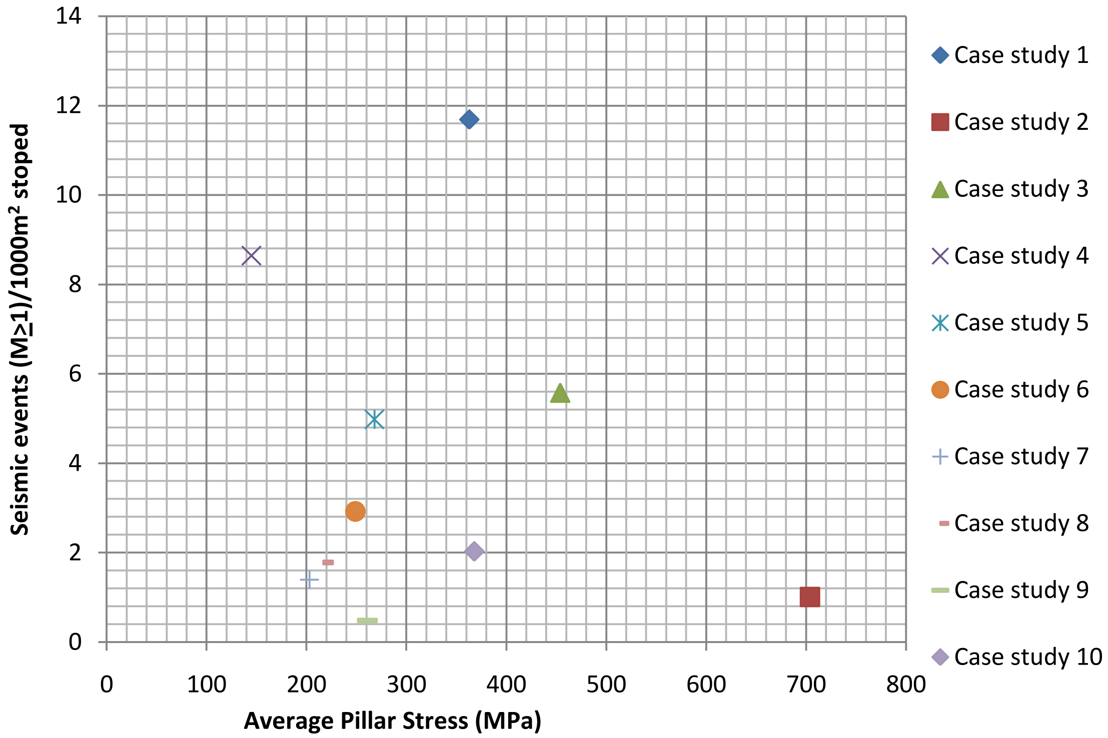
The obtained results will be used to assess whether it could be applicable for evaluating remnants in the Free State. In Graph 7.2 the average pillar stress (MPa) is plotted relative to the area of the remnant left to be mined. Limiting values are plotted on Graph 7.2 for the shale and the average strength for the Waxy Brown Quartzite and Upper Footwall Quartzite. The limiting value used for the shale, with a UCS of 60MPa, is 150MPa. The limiting value used for the foundation at these remnants for Waxy Brown Quartzite's and Upper Footwall Quartzite's, with an average UCS of 180MPa, is 450MPa. When assuming that the plotted seismic events, $M_L \geq 1.5$ as shown in Graph 7.2 indicate failure of the rock, the results indicate that remnants failed well before reaching an average pillar stress of 450MPa. However for the shale it would seem that failure does occur when the limiting criterion of 150MPa is exceeded.

It is clearly visible from Graph 7.2 that there is a significant difference in case studies 1 and 2 done on Harmony 2 Shaft when compared to the rest of the case studies done on Bambanani Mine. This is mainly due to the difference in mining span, which is in excess of 400m, around these two remnants on Harmony 2 Shaft. On Bambanani Mine there are numerous north-south geological structures with loss of ground reducing the mining span, which hardly ever exceeds 200m.

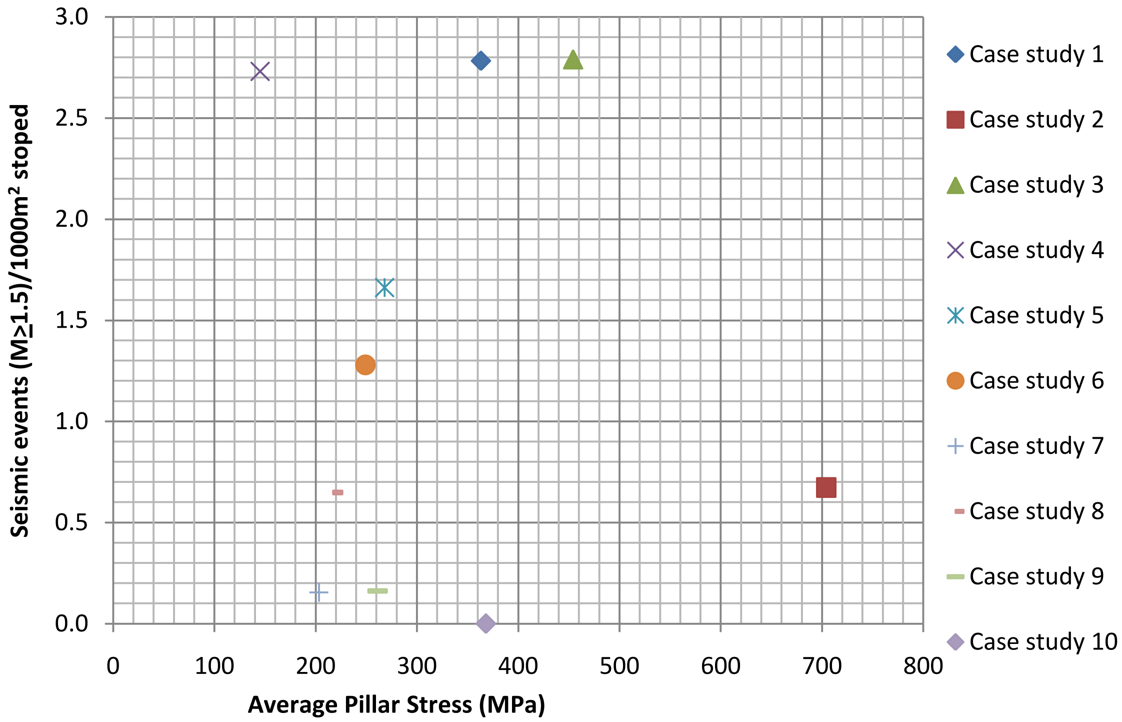


Graph 7.2 - Average Pillar Stress (MPa) versus Area (m^2).

In Graph 7.3 and Graph 7.4 the seismic events for $M_L \geq 1$ and $M_L \geq 1.5$ recorded per 1000m^2 stoped versus the average pillar stress are plotted respectively for the ten case studies. The obtained results in Graph 7.3 and Graph 7.4 indicate that there is no correlation between APS and the number of seismic events, $M_L \geq 1$ and $M_L \geq 1.5$ recorded per 1000m^2 stoped.



Graph 7.3 - Seismic events (M≥1) versus APS when mining remnants.



Graph 7.4 - Seismic events (M≥1.5) versus APS when mining remnants.

In Table 7.3 the maximum values obtained for average pillar stress for each case study are listed. From the results, the pillar strength failure criterion for the Waxy Brown Quartzite and Upper Footwall Quartzites of 450MPa is exceeded for 50% of the case studies. The pillar strength failure criterion for the Shale of 150MPa is exceeded for 100% of the case studies.

	Maximum APS (MPa)
Case study 1	393
Case study 2	947
Case study 3	586
Case study 4	1054
Case study 5	470
Case study 6	343
Case study 7	274.4
Case study 8	324.9
Case study 9	353.5
Case study 10	632

Table 7.3 - Maximum values obtained for average pillar stress for case studies.

The pillar strength criterion is mainly used for the evaluation of bord and pillar mining, pillar punching into the foundation and foundation failure of stabilizing pillars, and not for remnants. It is concluded that the use of the pillar strength criterion for remnants is unsatisfactory, due to the continuous change in dimensions of the remnant when being mined. Stabilizing pillars are designed with specific dimensions, and once created the pillar will remain intact for the life of mine. The average pillar stress results were relatively scattered for the remnants and thus could be ascribed to the difference in mining span, shape of remnants and depth below surface.

7.3. Energy Release Rate (ERR)

Energy release rate is a parameter that is used in the evaluation of mining layouts. Since its introduction in the 1960's it remains to this day the most acceptable parameter measuring the severity of conditions in deep mining as discussed in Section 5.2.[2]

In Figure 7.1 the seismic events recorded versus the energy release rate are plotted for the West Rand Mines, Southern Free State and Central Rand Mines. The data plotted in Figure 7.1 are from four longwall mines prior to the introduction of stabilizing pillars.

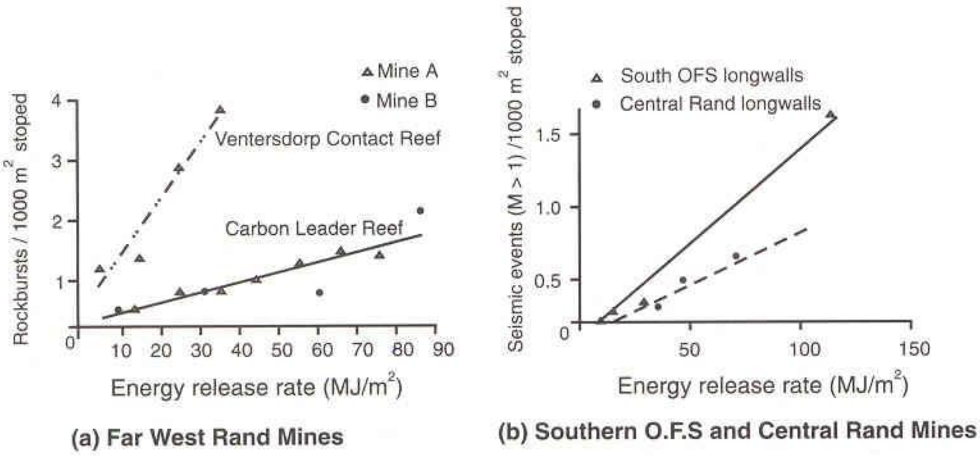
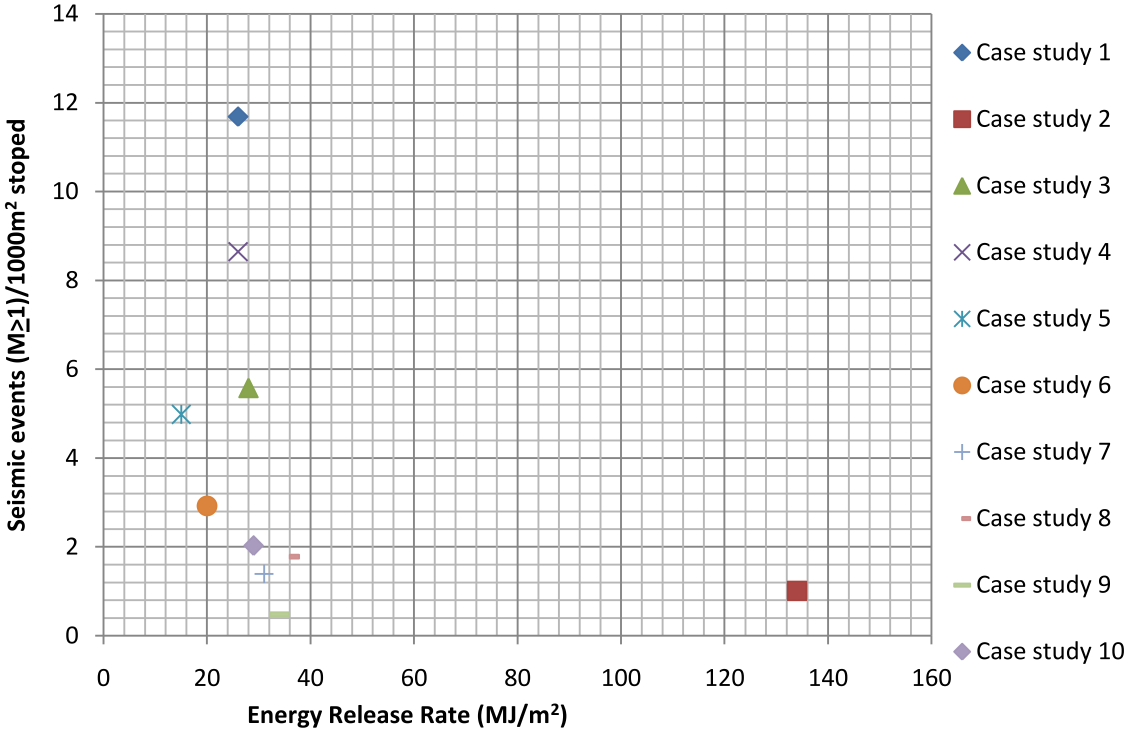


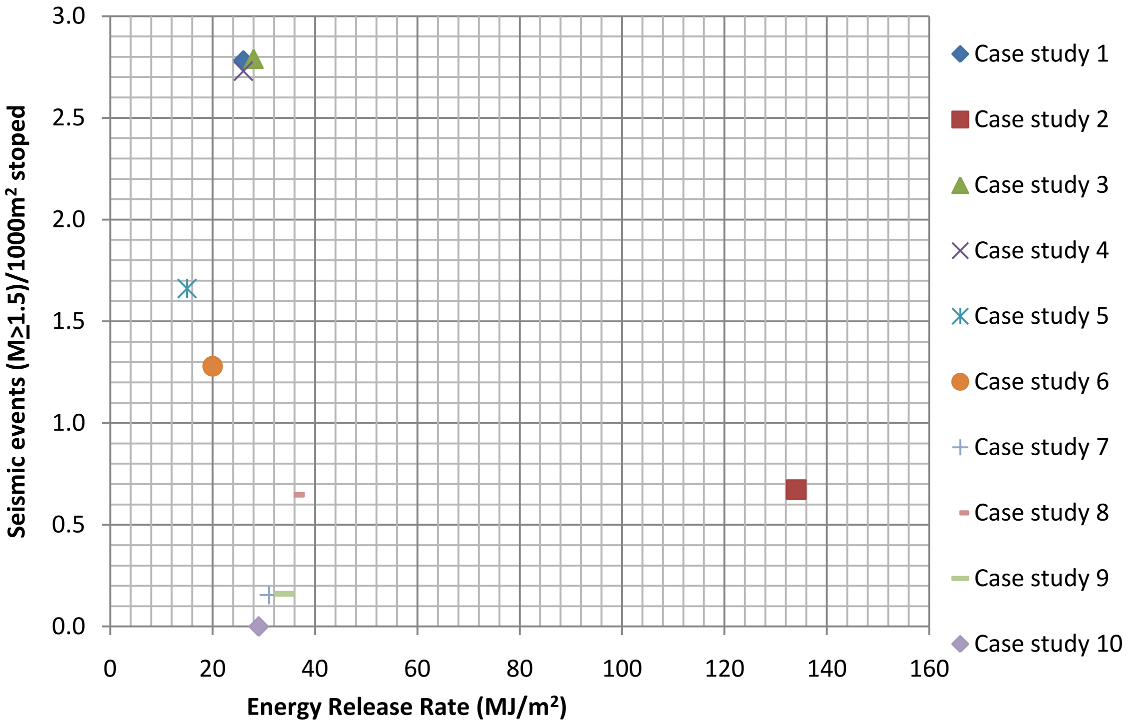
Figure 7.1 - Rockburst and seismicity versus ERR. Data from four longwall mines prior to the introduction of stabilizing pillars.[1]

The number of seismic events, $M_L \geq 1$ recorded per 1000m^2 stoped in the Free State versus ERR is plotted in Figure 7.1 (b) indicates that with increase in ERR there is an increase in the number of events. The conclusion was drawn from four case studies in the Free Sate that with increase in ERR, seismicity increases. It is however clear that the ERR values obtained in the Free State are extremely high when compared to the other regions. To be consistent, the same approach was taken in the present research as was the case in Figure 7.1. In Graph 7.5 the number of seismic events, $M_L \geq 1$ recorded per $1000m^2$ stoped at the ten case studies versus ERR is plotted. No trend was found from the results.

The same approach was taken for seismic events, $M_L \geq 1.5$. From these results, in Graph 7.6 the same conclusion was drawn, that there is no trend between the number of seismic events, $M_L \geq 1.5$ recorded per $1000m^2$ stoped for the ten case studies.



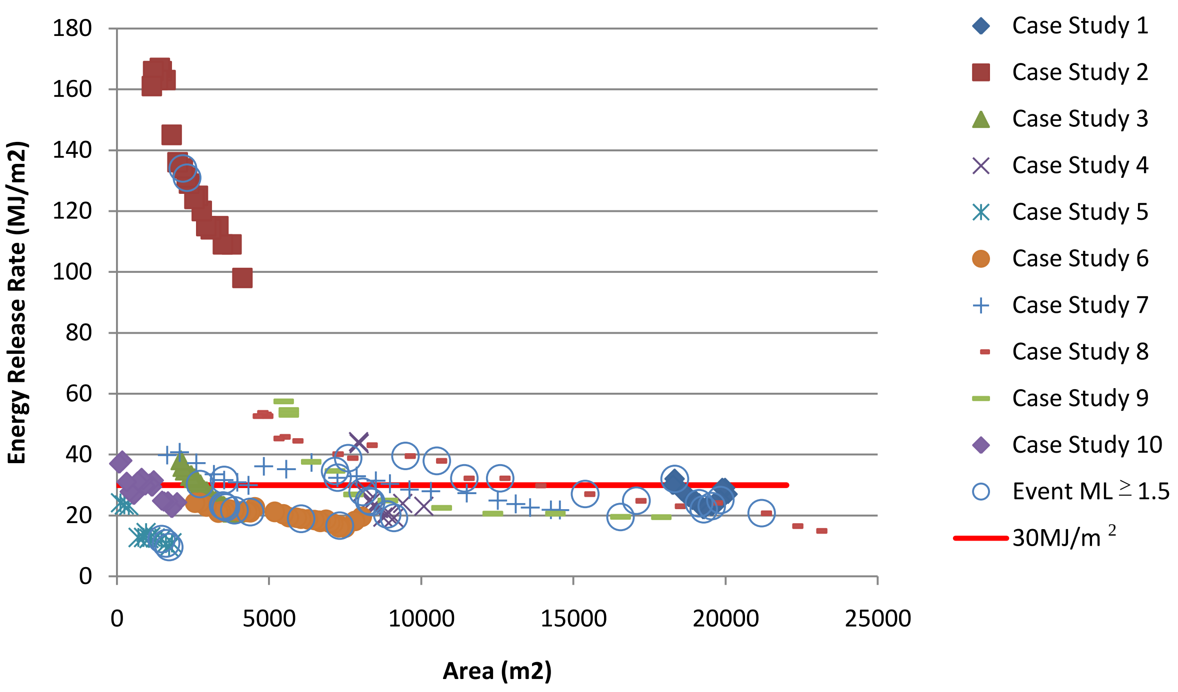
Graph 7.5 - Seismic events (M≥1) versus ERR when mining remnants.



Graph 7.6 - Seismic events (M≥1.5) versus ERR when mining remnants.

In Graph 7.7 the ERR is plotted for each mining step relative to the area of the remnant left to be mined. Assuming that the plotted seismic events, $M_L \geq 1.5$ as shown in Graph 7.7, indicate failure of the rock, the results indicated that 68% of the remnants failed before reaching the commonly acceptable limit of 30MJ/m^2. The results obtained for these remnants are scattered and no trend could be determined. On Harmony 2 Shaft it was found that the average ERR at the stope face was extremely high and this could be ascribed to the excessive mining spans during the numerical analysis and therefore the high stresses and closures calculated elastically.

For remnants on Bambanani Mine it was found that the average energy release rate did not exceed 60MJ/m^2. Although much greater than the 30MJ/m^2 as recommended by Jager and Ryder[1], no major face bursting was recorded or reported in these case studies.



Graph 7.7 - Energy Release Rate (MJ/m²) versus Area (m²).

	Maximum ERR (MJ/m²)
Case study 1	32
Case study 2	167
Case study 3	38.2
Case study 4	44.2
Case study 5	24.2
Case study 6	24.2
Case study 7	40.7
Case study 8	53.7
Case study 9	57.5
Case study 10	38

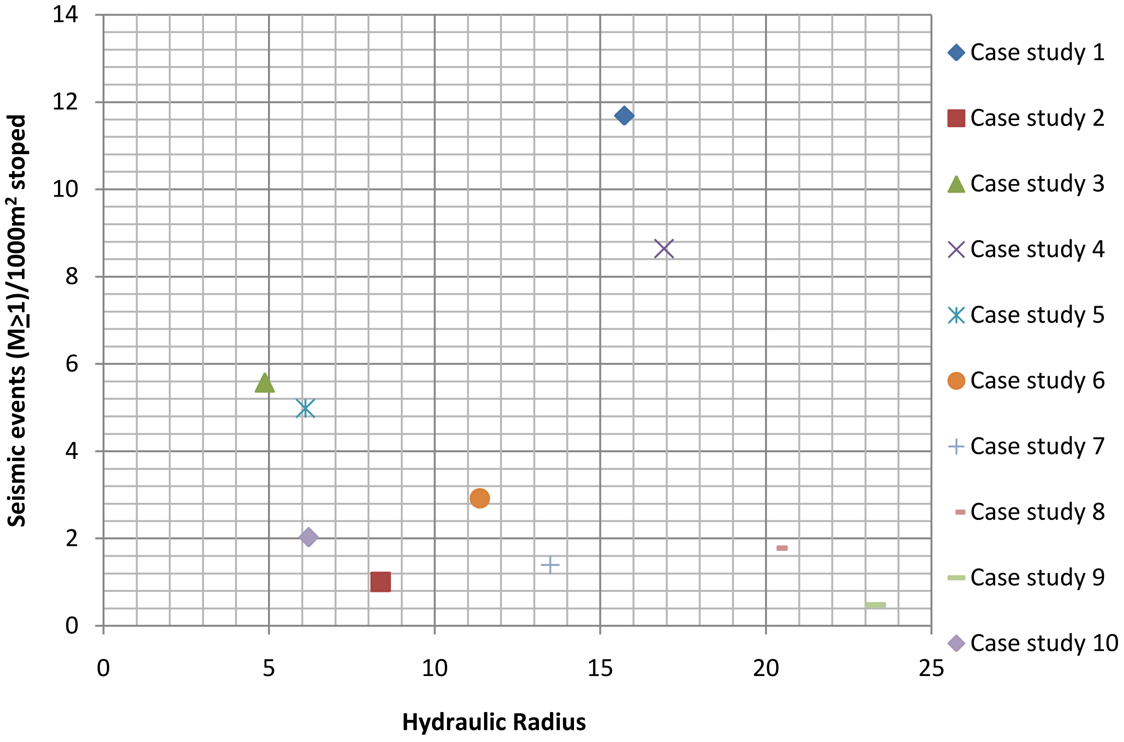
Table 7.4 - Maximum obtained value for energy release rate for case studies.

In Table 7.4 the maximum values obtained for energy release rate for each case study are listed. From the results, the energy release rate criterion is exceeded for 80% of the case studies.

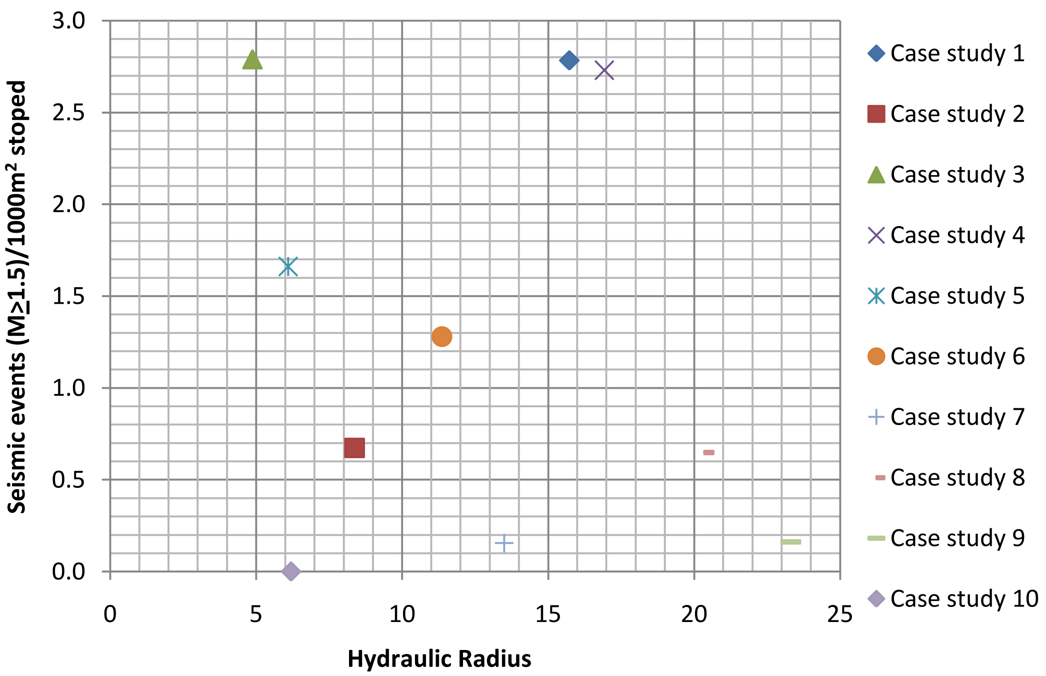
7.4. Hydraulic Radius

Hydraulic radius, also known as shape factor, describes the size of a block of ground to be mined as discussed in Section 5.5. The number of seismic events, $M_L \geq 1$ recorded per 1000m^2 stoped in the Free State versus Hydraulic Radius is plotted in Graph 7.8 and Graph 7.9. In Graph 7.8 the number of seismic events, $M_L \geq 1$ recorded per 1000m^2 stoped at the ten case studies versus Hydraulic Radius is plotted. No trend was found from the results for the number of seismic events, $M_L \geq 1$ recorded per 1000m^2 stoped versus Hydraulic Radius, at the ten case studies, as shown in Graph 7.8.

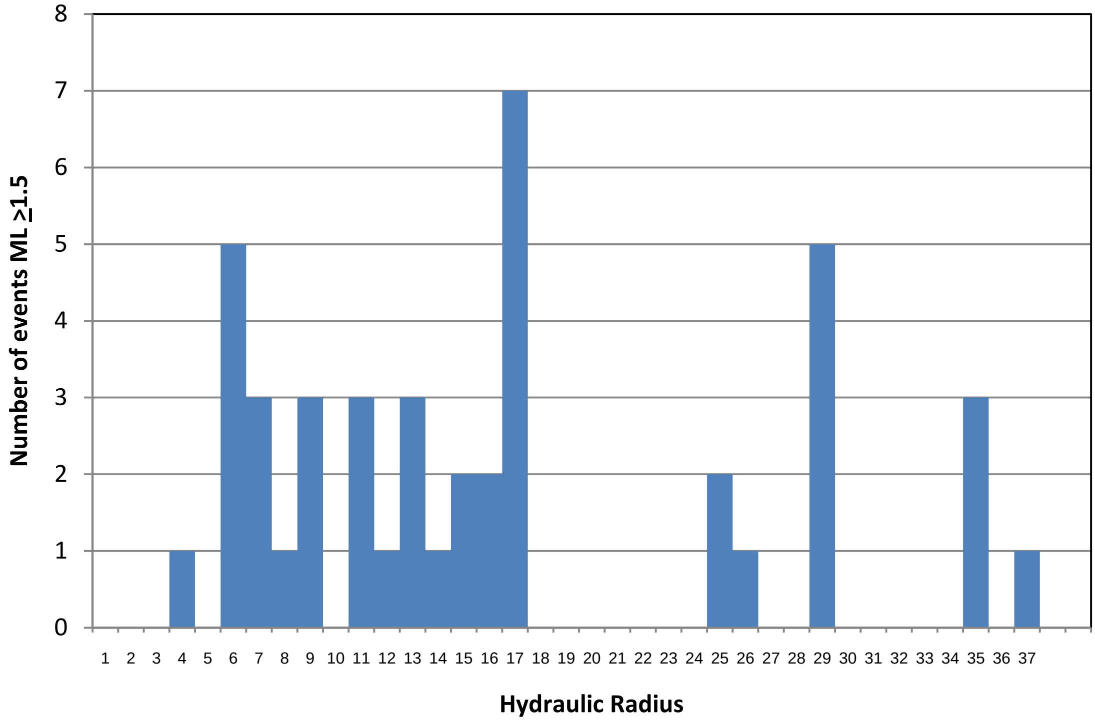
The same approach was taken for seismic events, $M_L \geq 1.5$ recorded per 1000m^2 stoped versus Hydraulic Radius at the ten case studies as shown in Graph 7.9. From these results the same conclusion was drawn that there is no trend between the number of seismic events.



Graph 7.8 - Seismic events (M≥1) versus Hydraulic Radius when mining remnants.



Graph 7.9 - Seismic events (M≥1.5) versus Hydraulic Radius when mining remnants.



Graph 7.10 - Number of events versus Hydraulic Radius.

Graph 7.10 shows the distribution of seismic events relative to hydraulic radius. From the results in Graph 7.10 there is no indication of a correlation between hydraulic radius and the occurrence of seismic events in remnants. This is most probably due to the fact that the remnants may be completely fractured or "crushed". It is concluded that hydraulic radius is not a satisfactory criterion for the evaluation of remnants in the Free State.

7.5. Mohr-Coulomb Failure Criterion

The Mohr-Coulomb failure criterion is discussed in Section 5.4, and was used to evaluate these case studies. The Mohr-Coulomb failure criterion can be mathematically expressed as: [31]

$$\sigma 1 = q\sigma 3 + \sigma_c \quad (7.1)$$

where $\sigma 1$ and $\sigma 3$ represent, respectively, the major and minor principal stresses, σ_c and q represent, respectively, the rock mass unconfined compressive strength and slope of the best fit-line[31] and

where $q = tan^2(45 + \frac{\varphi}{2})$; φ is the friction angle

To determine the failure criterion as shown in Equation 7.1 for the potential occurrence of rockbursts at remnants, the σ_1 and σ_3 values for a given seismic event that occurred at specific coordinates (x, y and z) for given mining steps. From this data a failure criterion for remnants can then be determined.

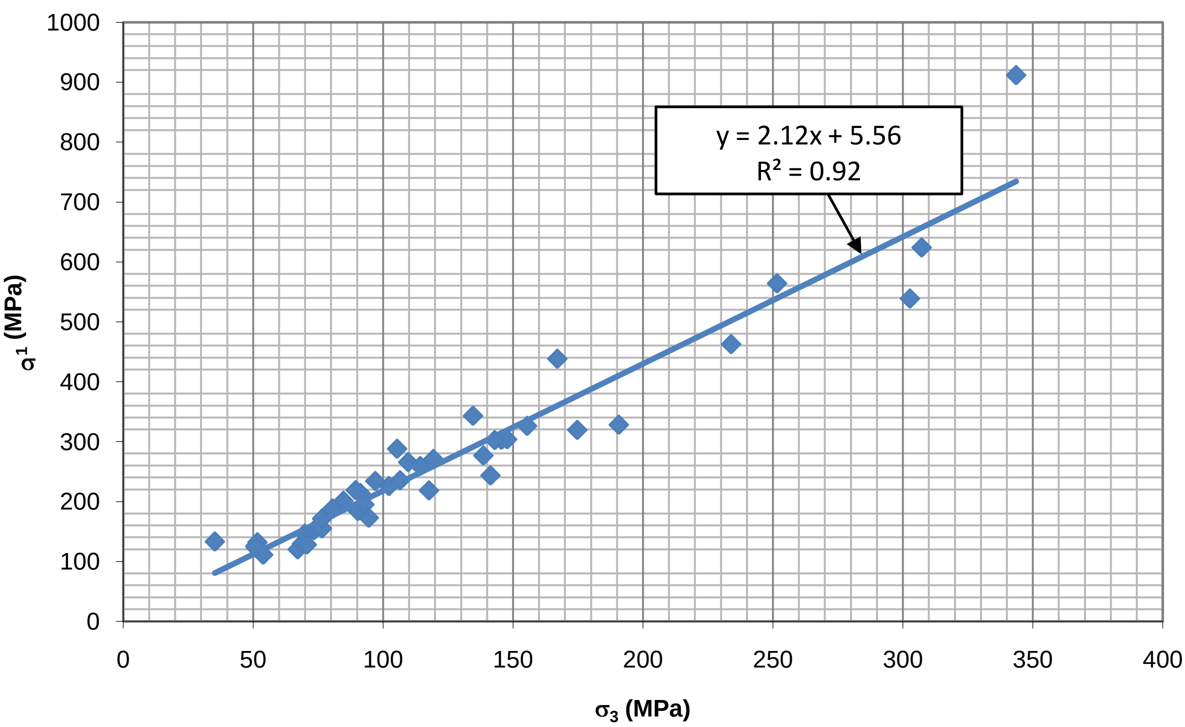
Potential occurrence of rockbursts is defined as follows:

where $\frac{\sigma 1}{(q\sigma 3+\sigma c)}$ is greater than 1, rockbursts will potentially occur.[31]

The assumption is that seismic events actually represent failure (occurrence of rockbursts) of the remnant. For this study only events with a local magnitude, $M_L \geq 1.5$ within the remnant were used. The reason for using only seismic events with a local magnitude, $M_L \geq 1.5$ is that with these events damage was usually observed.

In the numerical model the σ_1 and σ_3 stress values at specific coordinates (x, y and z) for the seismic events, at the respective mining steps, were obtained.

In Graph 7.11 the σ_1 and σ_3 stress values obtained from the analysis are plotted for each seismic event. When plotting all the σ_1 and σ_3 values obtained, it was found that there is a strong correlation between the prevailing stress at the time of each seismic event. From these values a failure criterion describing the potential occurrence of rockbursts at these remnants in the Free State could be derived, which is described by $\sigma_1 = 2.12\,\sigma_3 + 5.56$ as shown in Graph 7.11.

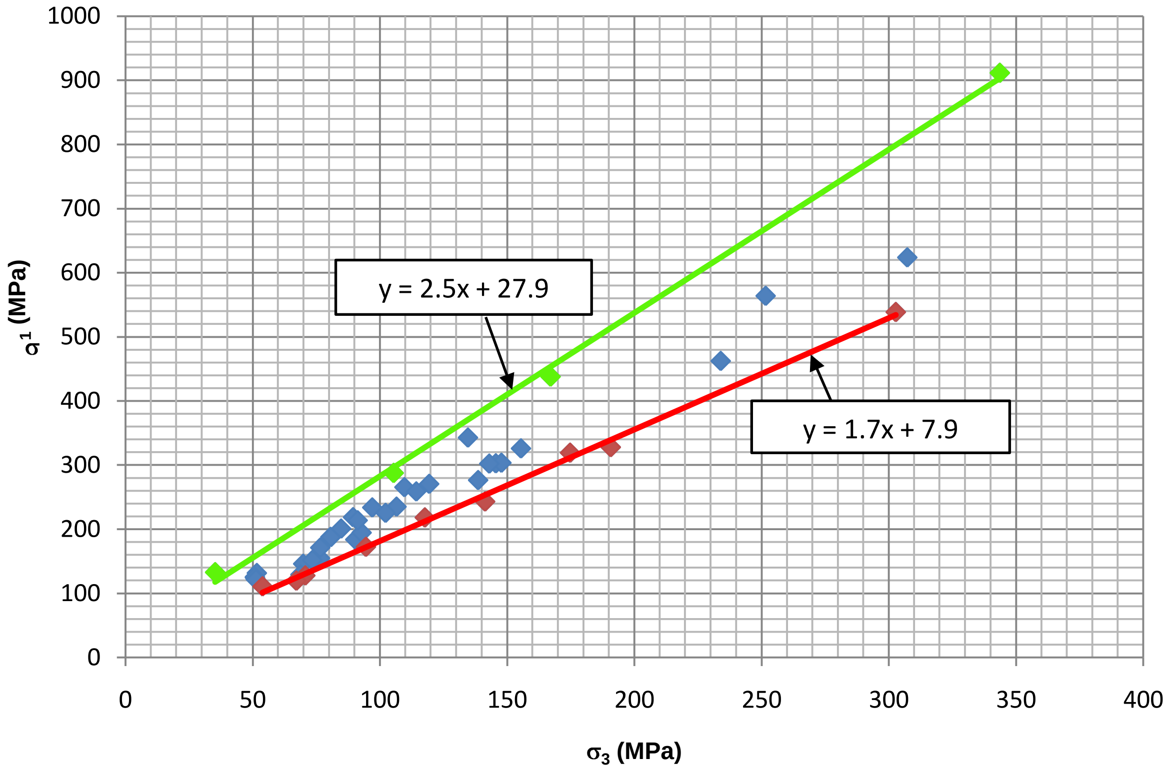


Graph 7.11 - Sigma 1 versus Sigma 3 values obtained from analysis.

Using the linear trend line, one finds that the mean error in prediction of σ_1 is approximately 45MPa. This gives a coefficient of variation of 17% as shown in Table 7.5, which is considered to be an acceptable variability.[31]

σ_1 (MPa)	σ_3 (MPa)	$\Delta\sigma_1$ (MPa)
146.21	69.86	7.45
342.98	134.62	-52.03
438.16	167.08	-78.40
218.85	89.46	-23.64
128.02	70.67	27.35
623.86	307.30	33.19
538.69	302.79	108.78
270.83	119.38	-12.19
462.44	233.97	39.13
265.68	109.65	-27.65
911.58	343.65	-177.48
328.09	190.74	81.84
111.07	53.87	8.69
124.65	50.90	-11.17
188.05	80.54	-11.75
131.85	51.64	-16.80
125.78	50.89	-12.34
121.88	51.25	-7.66
133.11	35.27	-52.77
184.05	90.33	13.02
154.96	76.50	12.79
218.41	117.68	36.64
151.96	73.44	9.30
172.71	94.50	33.19
119.93	67.16	28.00
287.91	105.41	-58.88
563.94	251.63	-24.92
129.38	68.78	22.00
276.67	138.62	22.77
243.35	141.34	61.85
319.34	174.77	56.72
302.82	145.57	11.35
171.43	76.57	-3.55
303.72	147.77	15.11
326.06	155.46	9.08
194.83	92.83	7.53
302.40	142.99	6.31
187.80	80.75	-11.06
235.28	106.55	-3.83
201.07	84.77	-15.80
234.06	97.01	-22.84
259.01	114.31	-11.11
213.96	91.28	-14.89
225.60	102.24	-3.29
$\overline{\sigma_1}$ = 263.46		q = 2.12
$\overline{\sigma_3}$ = 121.63		
s_1 = 157.96		
s_3 = 71.48		
s = 45.11		

Table 7.5 - Showing Sigma 1 and Sigma 3 values obtained from analysis results.



Graph 7.12 - Upper and lower limit trend lines.

The failure criterion σ_1 = 2.12 σ_3 + 5.56 describes the overall behaviour of the remnant case studies in the Free State. The scatter in the results allows upper and lower limits to the data to be defined, as shown in Graph 7.12. These upper and lower limits were fitted by eye. By selecting the lower range of σ_1 and σ_3 the lower limit is obtained by plotting the linear trend line expressed as y = 1.7x + 7.9, indicated in red. When selecting the upper range of σ_1 and σ_3 the upper limit is obtained by plotting the linear trend line expressed as y = 2.5x + 27.9, indicated in green.

From the study, a guideline for the safe extraction of remnants is proposed. This guideline only applies to mining of remnants in the Free State region. Lines defining upper and lower limits can be drawn describing the behaviour of remnants in the Free State as shown in Graph 7.13. When the σ_1 and σ_3 stresses in the remnant are plotted on this chart, remnant stability conditions can be defined as described below.

Stable remnants can be described as follows:

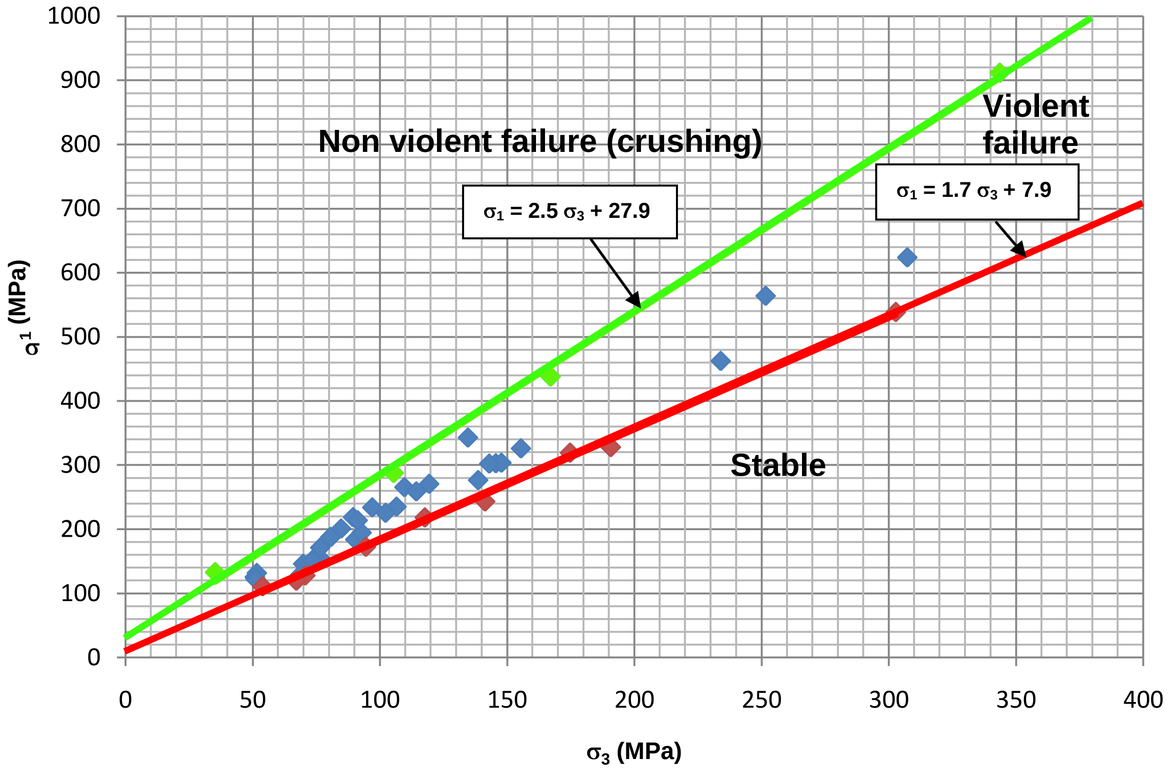
$\frac{\sigma 1}{(1.7\sigma 3 + 7.9)}$ < 1, situated below the remnant evaluation line indicated in red.

Violent remnant failure (potential occurrence of rockbursts) can be described as follows:

$\frac{\sigma 1}{(1.7\sigma 3 + 7.9)}$ > 1 < $\frac{\sigma 1}{(2.5\sigma 3 + 27.9)}$, situated between the remnant evaluation lines indicated in red and green.

Non violent failure (crushing) of remnants can be described as follows:

$\frac{\sigma 1}{(2.5\sigma 3 + 27.9)}$ > 1, situated above the remnant evaluation line indicated in green.



Graph 7.13 - Upper and lower limits for remnant failure in the Free State.

These upper and lower limits enable the practitioner to model the proposed mining layout for the remnant and identify possible areas within the remnant where violent seismic failure can occur. The Remnant Failure Index (RFI), based on the Mohr-Coulomb failure criterion, is proposed as a criterion to evaluate the potential occurrence of rockbursts at remnants.

When the *RFI* = $\frac{\sigma 1}{(1.7\sigma 3 + 7.9)}$ is greater than 1 the remnant will fail violently.

When the *RFI* = $\frac{\sigma 1}{(2.5\sigma 3 + 27.9)}$ is greater than 1 the case study results show that the potential occurrence of rockbursts is no longer possible.

Table 7.6 is a summary of how the behaviour of these remnants can be predicted using the following Remnant Failure Indexes.

Remnant behaviour	**Remnant Failure Index**
Stable	$\frac{\sigma 1}{(1.7\sigma 3 + 7.9)} < 1$
Violent failure	$\frac{\sigma 1}{(1.7\sigma 3 + 7.9)} > 1 < \frac{\sigma 1}{(2.5\sigma 3 + 27.9)}$
Non violent failure (crushing)	$\frac{\sigma 1}{(2.5\sigma 3 + 27.9)} > 1$

Table 7.6 - Showing behaviour of remnants in Free State for different Remnant Failure Indexes.

7.6. Application of the Remnant Failure Index (RFI)

In this section, the application of the newly developed Remnant Failure Index (RFI) will be discussed and it will be demonstrated how the obtained results can be implemented. Figure 7.2 shows the sequence of events that is followed and how remnants can be evaluated using the RFI.

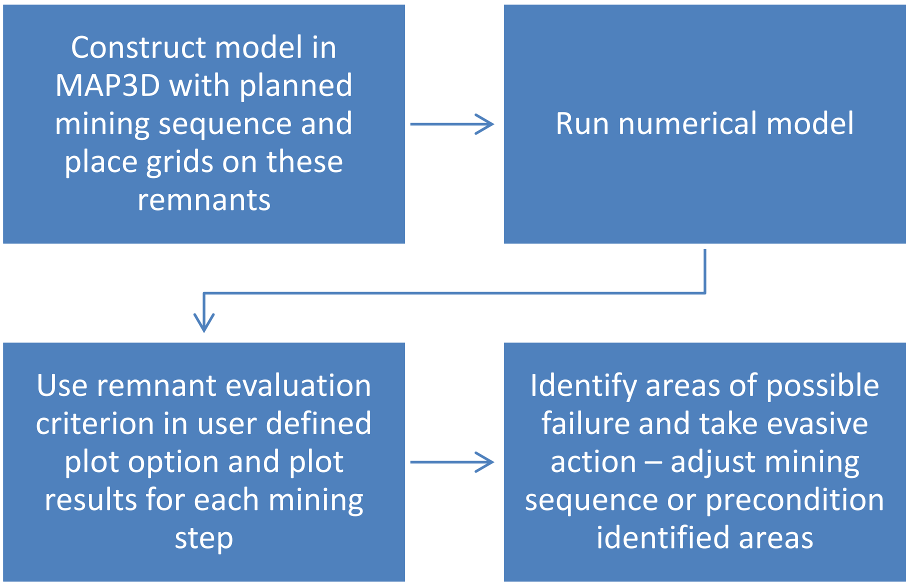


Figure 7.2 - Sequence of events for modelling remnants and applying the Remnant Failure Index.

Two of the ten remnant case studies were selected and modelled to determine if the newly developed RFI can be applied. Using the RFI for violent seismic failure at remnants (potential occurrence of rockbursts)

$$RFI = \frac{\sigma 1}{1.7\ \sigma 3 + 7.9}$$

areas most susceptible to violent seismic failure or the potential occurrence of rockbursts can be identified. The RFI was applied to case study 1 and case study 2. Using MAP3D-SV, grids were placed on each of the two case studies and analyzed. The RFI was applied by plotting the obtained results. It was found that areas of possible violent seismic failure or potential occurrence of rockbursts indicated in blue could be identified as shown in Figure 7.3 and Figure 7.4.

In Figure 7.3 and Figure 7.4, the blue lobes indicate areas where failure did not occur and light grey indicates areas already failed. From the analysis results it was found that the recorded seismic events plotted relatively close to the lobes of possible violent seismic failure or potential occurrence of rockbursts as shown in Figure 7.3 and Figure 7.4. Note that the location error of these seismic events is $\pm$30m as discussed in Section 5.4.

Although areas can be identified where potential rockbursts can occur, the actual time or current mining configuration when these seismic events may occur is still not known. The lobe of possible potential occurrence of rockbursts indicated is of great assistance as it enables the practitioner to determine the most probable position of seismic failure and resulting seismicity. Suitable methods of addressing and reducing the hazard can then be applied which can include:

- Implementation of preconditioning. [64]

- Deciding on the extent of remnant extraction (% extraction).
- Considering the best layout.
- Reviewing mining sequence and choosing the most appropriate one.

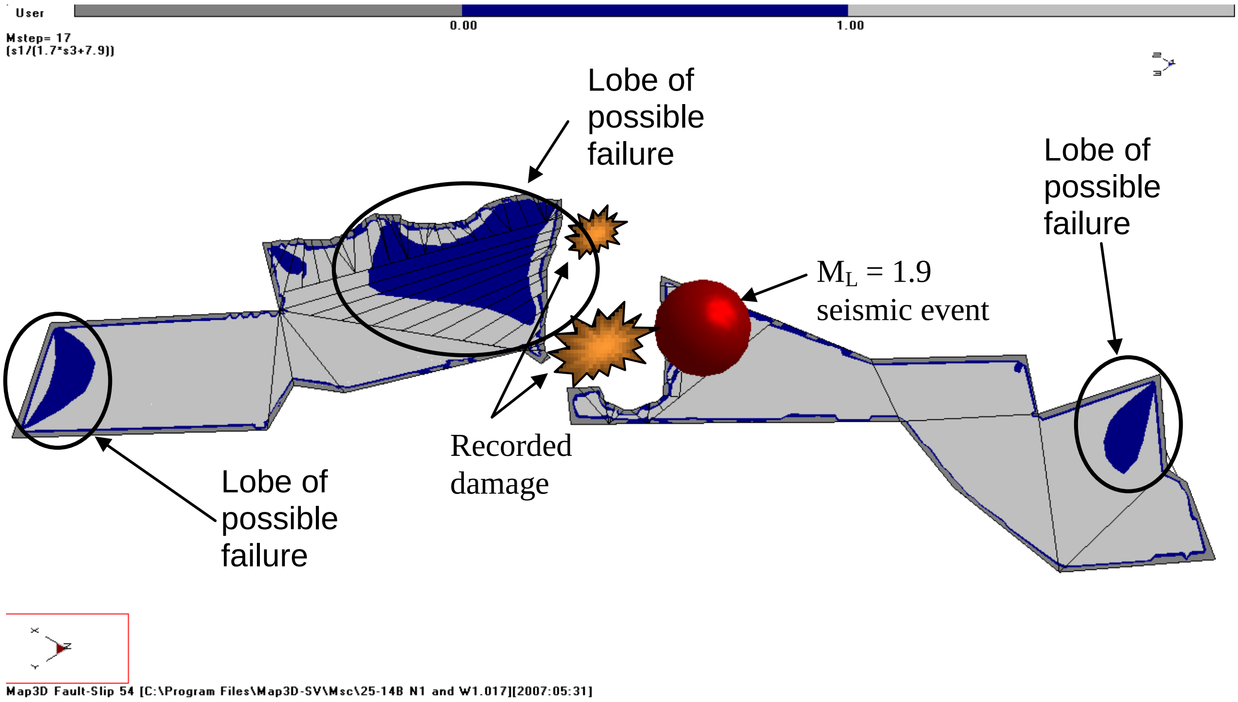


Figure 7.3 - The Remnant Failure Index used on case study 1.

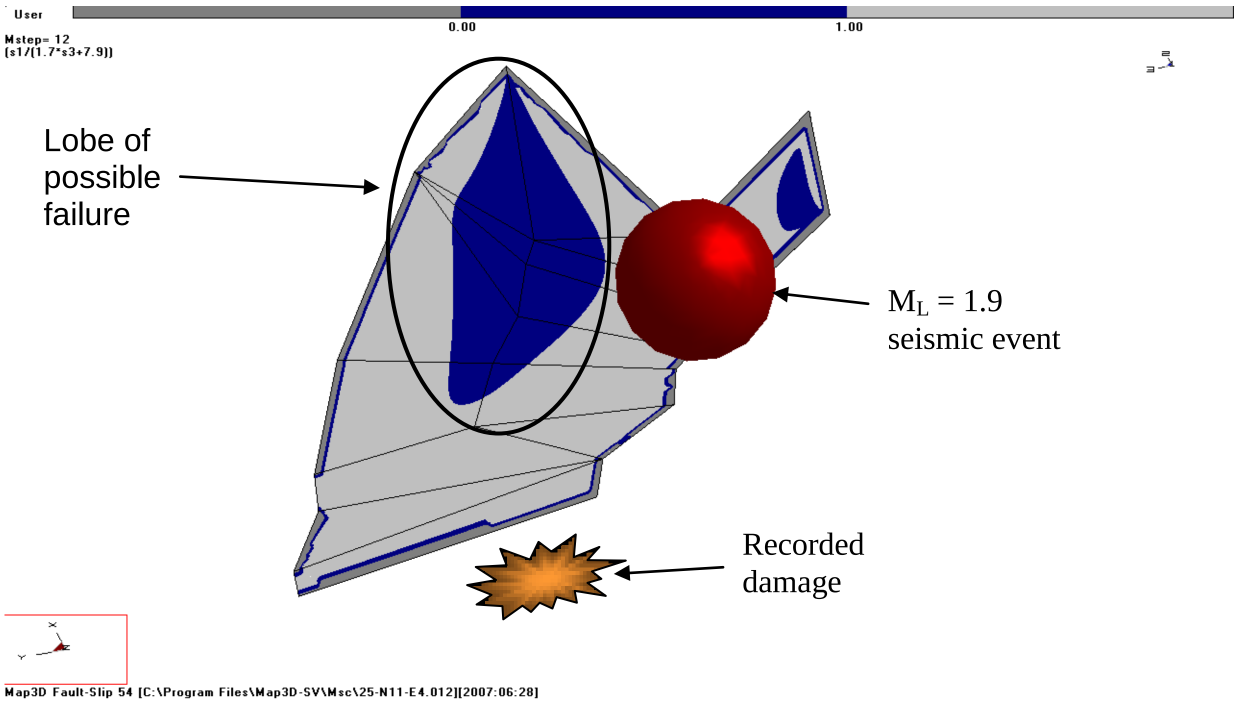


Figure 7.4 - The Remnant Failure Index used on case study 2.

8. Conclusions and Recommendations

The analysis results in Chapter 7 indicated that the use of average pillars stress, energy release rate and hydraulic radius was unsatisfactory for the evaluation of remnants. However from the results as discussed in Section 7.5, a remnant evaluation criterion, the Remnant Failure Index (RFI) for the safe extraction of remnants, based on the Mohr-Coulomb failure criterion, was proposed. This index will only apply to mining of remnants in the Free State region. [31]

When analyzing the σ_1 and σ_3 results obtained in Section 7.5 Table 7.5 for each seismic event at the time of the incident, it was found that there was a strong correlation between the stress states in the remnant at the time of each seismic event, which can be described by the following failure criterion [31]

$$\sigma_1 = 2.12\ \sigma_3 + 5.56$$

Using the linear trend line, one finds that the mean error in prediction of σ_1 is approximately 45MPa. This gives a coefficient of variation of 17% as shown in Section 7.5 Table 7.5, which is considered to be an acceptable variability.[31]

The failure criterion $\sigma_1 = 2.12\ \sigma_3 + 5.56$ describes the overall behaviour of the remnant case studies in the Free State. The scatter in the results allows upper and lower limits to the data to be defined, as shown in Section 7.5 Graph 7.8. The lower limit is expressed as $y = 1.7x + 7.9$, indicated in red and the upper limit is expressed as $y = 2.5x + 27.9$, indicated in green. Using RFI as a criterion to evaluate the rockburst failure of remnants, it was found that when the $RFI = \sigma_1 / (1.7\ \sigma_3 + 7.9)$ is greater than 1, the remnant will fail violently. When the $RFI = \sigma_1 / (2.5\ \sigma_3 + 27.9)$ is greater than 1, the case study results show that violent seismic remnant failure no longer occurs.

The RFI enables the practitioner to model the proposed mining layout for the remnant extraction and identify possible areas or lobes within the remnant where violent seismic failure may occur. Although areas can be identified where seismic events are likely to be located, the actual time or mining step when these events may occur is still not known.

Being able to identify these areas of possible violent seismic failure, preconditioning [64] can be used to de-stress the rock. Alternatively revised mining sequences and layouts of the remnants may be considered by modelling different mining scenarios and comparing them as discussed in Section 7.6. The application of the RFI to each alternative will then indicate which alternative is to be preferred.

It is recommended that future research should evaluate the applicability of the approach described in other mining areas such as the West Wits area. Future research can also investigate whether there is any correlation between the Local Energy Release Density (LERD)[39] and σ_3. Future research could also be done on the RFI to determine whether there is any correlation between the areas of the possible violent seismic failure lobes obtained and seismic event magnitudes.

9. References

1. Jager, A.J. and Ryder, J.A. (eds.) (1999)., *A Handbook on Rock Engineering Practice for Tabular Hard Rock Mines.* The Safety in Mines Research Advisory Committee (SIMRAC), Johannesburg.

2. Ryder, J.A. and Jager, A.J. (eds.) (2002)., *A Textbook on Rock Mechanics for Tabular Hard Rock Mines.* The Safety in Mines Research Advisory Committee (SIMRAC), Johannesburg.

3. Budavari, S. (1983)., *Rock Mechanics in Mining Practice.* The South African Institute of Mining and Metallurgy, pp.33 – 131.

4. Ryder, J.A. (1988)., *Excess Shear Stress in the Assessment of Geologically Hazardous Situations.* Journal of the South African Institute of Mining and Metallurgy, vol. 88, no 1, pp.27 – 39.

5. Napier, J.A.L. (1987)., *The Application of Excess Shear Stress to the Design of Mine Layouts.* Journal of the South African Institute of Mining and Metallurgy, vol. 87, no 12, pp.397 – 405.

6. Diering, J.A.C and Stacey, T.R., (1987)., *Three-dimensional Stress Analysis: a Practical Planning Tool for Mining Problems.* APCOM 87. Proceedings of the Twentieth International Symposium on the Application of Computers and Mathematics in the Mineral Industries. Volume 1: *Mining.* Johannesburg, SAIMM, pp 33- 42.

7. Starfield, A.M. and Cundall P.A., (1988)., *Towards a Methodology for Rock Mechanics Modelling.* Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. Vol. 25, No. 3. pp. 99 – 106.

8. Brook, N., (1985)., *The Equivalent Core Diameter Method of Size and Shape Correction in Point Load Testing.* Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. Vol. 22, No. 2. pp. 61 – 70.

9. Working Group on Revision of the Point Load Test Method., (1985)., *International Society for Rock Mechanics, Commission on Testing Methods.* Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. Vol. 22, No. 2. pp. 51 – 60.

10. Sharp, R., (27 March 1987)., *Generalised Description of the Geological Succession at President Steyn Mine*., Unpublished internal report.

11. Rangasamy, T. and Jager, A.J., (6 September 2002)., *A Selective Review of Remnant Definitions and Creation in the South African Gold Mining Industry*, SANIRE Symposium, Re-Defining The Boundaries.

12. International Society for Rock Mechanics, Commission on Terminology, Symbols and Graphic Representation, *Terminology (English, French, German),* Final Draft: July 1975

13. Kataka, M.O., Hildyard, M.W. and Sellers, E.J., (2003)., *Integration of Seismic Observations from Deep Level Gold Mines with Dynamic Numerical Modelling*., ISRM 2003 – Technology Roadmap for Rock Mechanics, South African Institute of Mining and Metallurgy., pp. 617 – 622.

14. Hanekom, J.W.L., (2003)., *A Design Protocol for Mining Remnants in Hard Rock Mining Operations Utilising a Rock Mass Classification System*., ISRM 2003 – Technology Roadmap for Rock Mechanics, South African Institute of Mining and Metallurgy., pp. 475 – 480.

15. Bosman, J.D. and Van Aswegen, G., (2003)., *Dynamic Failure of Pillars Remnants – Case Studies.,* ISRM 2003 – Technology Roadmap for Rock Mechanics, South African Institute of Mining and Metallurgy., pp. 143 – 149.

16. Cockram, M.J., Makinen, E.O. and Kirsten, H.A.D., *A Methodology to Quantify Risk and an Application to Remnant Mining*, South African Institute of Mining and Metallurgy, Second International Seminar on Deep and High Stress Mining., pp. 147 – 158.

17. Vieira, F.M.C.C. and Durrheim, R.J., (2001)., *Probabilistic Mine Design Methods to Reduce Rockburst Risk.* Rockburst and Seismicity in Mines – RaSiM5, South African Institute of Mining and Metallurgy, 2001. pp. 251- 262.

18. Spottiswoode, S.M., (1997)., *Energy Release Rate with Limits to On-Reef Stress*. SARES97, 1st Southern African Rock Engineering Symposium Proceedings, Johannesburg, South Africa., pp. 252 – 258.

19. Watermeyer, G.A. and Hoffenberg, S.N., (1932)., *Witwatersrand Mining Practice.,* pp. 393 – 403.

20. Hill, F.G., (1944)., *A System of Longwall Stoping in a Deep-Level Mine, with Special Reference to its Bearing on the Pressure Burst and Ventilation Problems.* Association of Mine Managers of the Transvaal, Papers and Discussions, 1942 – 1945, Volume1., pp. 257 –276

21. Roberts, D.G., (1952)., *Observations on Ground Behaviour Associated with Mining the Carbon Leader on Blyvooruitzicht G.M Co., Together with Some Notes on the Removal of Remnants*. Association of Mine Managers of the Transvaal, Papers and Discussions, 1952 – 1953., pp. 187 –218

22. Van Der Wal, H.J. and Macaulay, R.J., (1968)., *Up-Dip and Remnant Mining as Practised on West Rand Consolidated Mines, Ltd.* Association of Mine Managers of South Africa, Papers and Discussions, 1968 – 1969., pp. 471 – 488

23. Berrange, C.L., *North Face Method of Remnant Extraction*. Association of Mine Managers of South Africa, Papers and Discussions, 1956 – 1957., pp. 199 –220

24. COMRO, *An Industry Guide to Methods Of Ameliorating the Hazards of Rockfalls and Rockbursts,* 1988., pp. 12 – 16, 33

25. Wilson, J.W. and More-O'Ferrall, R.C., *The Application of the Electrical Resistance Analogue to Mining Operations.* Association of Mine Managers of South Africa, Papers and Discussions, 1968 – 1969., pp. 209 – 280

26. *Oxford English Dictionary.* Second Edition 1989.

27. Wiles, T.D., Personal Communication., 26 September 2006.

28. Lucas, J., Personal Communication., 11 April 2007.

29. Brentley, K. R., Personal Communication., 11 April 2007.

30. Pretorius, M., Personal Communication., 14 August 2007.

31. Wiles, T.D., (2006)., *Reliability of Numerical Modelling Predictions*, International Journal of Rock Mechanics and Mining Sciences, V43., pp. 454-472.

32. Wiles, T.D. MAP3D User's Manual, Mine Modelling Report, 2006.

33. Wiles, T.D. Course Notes, Mine Modelling Report, 2006.

    36-a Part 1: Numerical Modelling Background

    36-b Part 2: Rock Mechanics Model Interpretation

    36-c Part 3: Energy Release Rate/Loading System Stiffness/Non-Linear Modelling

    36-d Part 4: Integration of Modelling with Seismic Monitoring

    36-e Part 5: Model Calibration

34. Wiles, T.D., (2005)., *Rockburst Prediction Using Numerical Modelling: Realistic Limits for Failure Prediction Accuracy*, 6th International Symposium on Rockbursts and Seismicity in Mines (RaSiM 6), Perth, Australia.

35. Wiles, T.D., Villaescusa, E. and Windsor, C.R., (2004)., *Rock Reinforcement Design for Overstressed Rock Using Three Dimensional Numerical Modelling*, 5th Int. Symposium on Ground Support in Mining and Underground Construction, Perth, Australia.

36. Wiles, T.D., (2002)., *Loading System Stiffness – a Parameter to Evaluate Rockburst Potential*, First International Seminar on Deep and High Stress Mining, Australian Centre for Geomechanics, Perth, Australia.

37. Wiles, T.D., Lachenicht, R. and van Aswegen, G., (2001)., *Integration of Deterministic Modelling with Seismic Monitoring for the Assessment of Rockmass Response to Mining: Part I Theory*, Proc. of the Fifth International Symposium on Rockburst and Seismicity in Mines (RASiM5), Johannesburg, South Africa., pp. 379-388.

38. Lachenicht, R., Wiles, T. and van Aswegen, G., (2001)., *The Integration of Numerical Modelling with Seismic Monitoring through the MAP3Di Boundary Element Method: Part II Applications*, Proc. of the Fifth International Symposium on Rockburst and Seismicity in Mines (RASiM5), Johannesburg, South Africa., pp. 389-398.

39. Wiles, T.D., (1998)., *Correlation Between Local Energy Release Density and Observed Bursting Conditions at Creighton Mine*, Mine Modelling Report.

40. Mariset, S.D., Wiles, T.D. and. Martin, C.D., (1997)., *Energy Release Rate Study for Deep Level Mine Development at Creighton Mine*, Mine Modelling Report.

41. Wiles, T.D., (1995)., *DBEM3D Back-Analysis of AECL's Mine-by-Experiment*, Mine Modelling Report.

42. Wiles, T.D. and Kaiser, P.K., (1994)., *Failure Process Modelling - a Fracture Mechanics Approach to Discing*, Laurentian University.

43. Wiles, T.D. and Kaiser, P. K., (1994)., *In Situ Stress Determination Using the Under-Excavation Technique - Part I: Theory*, Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., Vol. 31, No.5., pp. 439-446.

44. Wiles, T.D. and Kaiser, P. K., (1994)., *In Situ Stress Determination Using the Under-Excavation Technique - Part II: Applications*, Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., Vol. 31, No.5., pp. 447-456.

45. Wiles, T.D., (1991)., *Issues of Ease of Use, Error and Accuracy Control in MAP3D, Mining Analysis Program in 3-Dimensions*, Proc. 2nd Canadian Conference on Computer Applications in the Mineral Industry, Vancouver, B.C., pp. 669-677.

46. Wiles, T.D. and MacDonald, P., (1990)., *Rock Mechanics Aspects of Regional Faulting Around Creighton Mine*. 31st U.S. Rock Mechanics Symposium, Golden, Colorado.

47. Wiles, T.D. and Kaiser, P. K., (1990)., *A New Approach for Statistical Treatment of Stress Tensors*, Specialty Conference on Stress, Ottawa, Ontario.

48. Wiles, T.D., (1990)., *Plasticity in the Boundary Element Method*. Year 1, 2 and 3 Interim Report on Numerical Modelling. DSS file no. 14SQ.23440-6-9033.

49. Wiles, T.D., (1989)., *Non-Linear Modelling of Mining at Great Depth: A Case History at Creighton Mine*. Int. Symposium Rock Mechanics, Pau, France, V 2., pp. 621-628.

50. Wiles, T.D. and MacDonald, P., (1988)., *Correlation of Stress Analysis Results with Visual and Microseismic Monitoring at Creighton Mine*, Computers and Geotechnics, Vol. 5, No. 2., pp. 105-122.

51. Wiles, T.D., (1988)., *Accuracy and Applicability of Elastic Stress Analysis Methods in Mining*, 15th Canadian Rock Mechanics Symposium, Toronto, Canada., pp. 207-220.

52. MacDonald, P., Wiles, T. and Villeneuve, T., (1988)., *Rock Mechanics Aspects of Vertical Retreat Mining at 2000m Depth at Creighton Mine Canada*. Conference on Applied Rock Engineering, Inst. Min. and Metallurgy, London, England., pp. 151-157.

53. Oliver, P., Wiles, T. and MacDonald, P., (1987)., *Rockburst Control Measures at INCO's Creighton Mine*. Proc. 6th Conf. Ground Control in Mining, West Virginia, USA.

54. Wiles, T.D. and J.H. Curran, A General 3-D Displacement Discontinuity Method, Proc. 4th Int. Conf. Numerical Methods in Geomechanics, V1, 1982, pp. 103-111.

55. Vista Local paper, Goldfields, Free State, Special Anniversary Edition, April 1997.

56. Code of Practice Harmony 2 Shaft.

57. Lucas, J., (2005)., *Report on the Rockburst Fatal on Harmony 2 Shaft*, Unpublished Internal Report.

58. Applegate, J.D., (1991)., *Rock Mechanics Aspects of Sequential Grid Mining*.

59. Louw, D., Personal Communication., 22 March 2006.

60. Le Roux, P.J., (2004)., *Project on Rock Mass Properties for the Free State*, Mechanical Properties of Rocks and Rock Masses, University of the Witwatersrand, South Africa.

61. Turner, C., (2006)., *Avroy Shlain Diary.*, pp.203

62. Poster of: *The Witwatersrand Basin, Surface and Subsurface Geology and Structure.*

63. Brown, E.T., *Block Caving Geomechanics*, The International Caving Study I 1997 – 2000, JKMRC Monograph Series in Mining and Mineral Processing 3., pp. 127-138.

64. Toper, A. Z., Stewart, R. D., Kullmann, D. H., Grodner, M., Lightfoot, N., Janse van Rensburg, A. L. and Longmore, P. J., (1998)., *Develop and Implement Preconditioning Techniques to Control Face Ejection Rockbursts for Safer Mining in Seismically Hazardous Areas,* GAP336 Final Report, CSIR Division Mining Technology.

65. Brady, B.H.G., and Brown, E.T., (1985)., *Rock Mechanics for Underground Mining*, pp. 107-109.