SAFETY IN MINES RESEARCH ADVISORY COMMITTEE

SIMRAC

Final Project Report

Title: MINING HIGHLY STRESSED AREAS

Part 1: Chapters 1 - 10

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Research
Agency: CSIR: Division of Mining Technology

Project No: GAP 033

Date: December 1995

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EXECUTIVE SUMMARY

The aim of this long-term project has been to focus on the extreme high-stress end of the mining spectrum. Such high stress conditions will prevail in certain ultra-deep mining operations of the near future, and are already being experienced in extracting remnants, stabilizing pillars or shaft pillars at more moderate depths. Mining in such ground poses major problems including high rates of closure and ground mobility, difficulties of siting and support of access tunnels, and above all, severely enhanced hazards of rockbursting.

An industry wide questionnaire, a comprehensive literature review and a high level industry workshop assisted in identifying priority areas of work for this project. These were to develop new and improved layouts and regional mining strategies to satisfy indicated mining and geotechnical conditions, to study remnant stability with a view to reducing remnant associated problems and to develop improved seismic techniques. In addition a number of promising concepts beyond the scope of this project have been identified and are listed in the future work section.

Anticipated mining conditions at depths between 3000 and 5000m have been investigated and are given in detail in this report. These include energy release rate (ERR), stope closure rates, face area stresses and excess shear stress values. Considerable information on the geotechnical environment of orebodies potentially mined at ultra-depth have been collected, much in database form. This information includes reef information such as channel width and grade; hangingwall and footwall composition and associated properties; fault and dyke distribution and projected future production trends with depth. These provide essential information for future mine layout planning and assessment.

Laboratory work has been carried out to quantify the post-failure behaviour of brittle quartzite alone as well as with the confining effects of backfill. This work is in anticipation of the use of crush pillars and backfill as a useful support medium and mining method for application at ultra-depth.

Several new mine layouts and approaches are proposed for the ultra-depth conditions indicated in a geotechnical classification. New regional and local layouts and mining methods are described that provide increased worker safety at ultra-depth. These offer significantly reduced ERR, increased extraction, reduced stope closure and face stress compared to the best methods currently employed.

A detailed assessment of remnant stability by back analysing a number of problematic remnants has yielded disappointing results.

Seismic software enhancements offer substantially improved locations and event classification. This has significant potential in advance identification of hazardous geological features and will be of benefit to ultra deep level mining.

1. BACKGROUND AND MOTIVATION

The aim of this long-term project has been to ensure that existing research and development activities are focused adequately towards the extreme high-stress end of the mining spectrum, and to ensure that further, possibly very radical, concepts for mining in these conditions are addressed where appropriate.

Highly-stressed ground may be defined as ground in which the stresses exceed about one-half of the UCS of the host rock. Mining in such ground poses major problems : of having to cope with high rates of closure and ground mobility, difficulties of siting and support of access tunnels, and above all, severely enhanced hazards of rockbursting. Such conditions prevail in certain ultra-deep mining operations of the near future, and are already being experienced in a number of mines which, in order to maintain their productive lives, are faced with the necessity of extracting remnants, stabilizing pillars, or deep shaft pillars.

R&D strategies to address these problems are already largely in place : the in-depth study of support/rockmass interactions to enable the development of fully rational support design criteria, the development and evaluation of improved face-area support and stiff backfill systems and of rockburst-resistant support for both stopes and tunnels, the development of regional numerical modelling programs which encompass non-linear and seismic rockmass behaviour, and the development and evaluation of appropriate rockmass preconditioning and fault-slip rockburst control techniques. At present, these strategies are largely aimed towards current mining conditions and practices. But the long-term future of many individual mines, and of the Industry itself, demands that additional attention be paid to addressing the more extreme stress environments. The following areas of work are indicated from work to date and from discussions with industry personnel.

The mining method, layout, local and regional support requirements for mining in high stress/ultra-deep conditions are strongly influenced by the prevailing geotechnical conditions (e.g. depth, dip, channel width, grade distribution, rockmass and reef properties, degree of geological disturbance (faults, dykes, joints), much of which may be learned in advance of mining). Such available information should be collated for current, proposed and possible ultra-deep mines. This is seen as an important pre-requisite; guiding further work in this area.

It is also clear that improved regional support and layout designs are required for ultra-deep mining - to limit seismic energy release; reduce stope closure; reduce face stress. Cook and Salamon (1966) motivated the introduction of stabilizing pillars for deep-level stope support as follows: "As mining extends to greater depths, the frequency and severity of rockburst is likely to increase. It appears that a substantial reduction in the rockburst hazard can be achieved only by radical changes in the present stoping method." They further point out that such mooted radical changes need only apply to mines that are unable to achieve adequate improvements using current support. As mining at ultra-depth is considered, both "radical alternatives" and improved use of current

support methods need to be examined and evaluated. The performance of current and improved regional support elements and combination (crush and squat pillars, backfill and concrete) should be evaluated, initially using laboratory and numerical techniques; with promising concepts pursued further in underground trials.

The considerable difficulty in extracting remnants, particularly those adjacent to geological features motivates the assessment of seismic and other parameters which may provide suitable indicators for how and when such areas can be safely extracted. In addition there are a number of parallels between remnant conditions and ultra-deep mining which should be identified as they may prove useful for simulating ultra-depth conditions.

An ongoing low-level programme of upgrading of seismic software has been carried out. These improvements assist practitioners at the mines towards understanding their rockburst problems in a more quantitative sense : the identification and nature of specific seismically hazardous structures, the identification of times when seismic hazards become particularly high, and the impact this information could have on optimum support and layout planning.

Increasing problems associated with deeper mining have led to questioning the viability of mining in excess of 3000m. In essence then the objective of this project is to:
- investigate improved regional support and rockburst control techniques for ultra-depth,
- improve layouts applicable to high stress conditions,
- improve seismic monitoring and analysis procedures.

2. PROJECT DIRECTION

The first objective of this project was to identify problems associated with high stress mining. This was done by completing and analysing a questionnaire, by reviewing relevant literature and by discussion with senior rock engineering personnel at an industry workshop. The principal findings of these are summarised below, with detailed reports given in Appendices 1 - 3. These results had a formative influence on the project direction, specifically in the area of alternate mining methods, assessment of remnant stability and in the development of enhanced seismic techniques.

2.1 Questionnaire - results summary

A questionnaire related to mining at great depth and in very high stress conditions was been completed with the assistance of mine rock mechanics personnel on over twenty mines in all mining districts. The objective of the questionnaire was to identify and where possible, quantify problems associated with deep level and high stress mining taking place at present as well as anticipated problems in the future.

The questionnaire results are best summarised in the following tables, with a complete assessment in Appendix 1.

	% production from remnants & isolated ...	Remnants, isolated blocks, difficult to mine ...								
		Bursting	Access problems	Faults & dykes	Longwall seismicity	Face stress	Seismic data avail.	# pillars presently mined	# pillars future	Easier to mine with time
Klerksdorp	44% increasing	X	X NB	X		X	X	2	2	X
Far West Rand	20% constant	X			X	X	X	4	many	X
Central Rand	20% increasing					X		1	some	
OFS	25%		X	X			X	2	3	
Evander	25% increasing		X						1	X

	Mining method			Regional support						Stope support				
	Scattered	Longwall	Pillar	Backfill	Pillars	Geology	Remnant	Bracket	Caving	Bolts	RYHP	Elongate	Backfill	Packs
Klerksdorp	X		X	X	X	X	X	X	X		X	X	X	X
Far West Rand	X	X	X	X	X	X	X	X			X	X	X	X
Central Rand	X	X	X	X	X	X	X				X		X	
OFS	X	X	X			X	X	X			X	X	X	X
Evander	X					X	X			X				X

	Seismicity						Off-reef problems			Geology & other problems	
	Max. Mag	Assoc. faults	Assoc. dykes	Assoc. pillars	Assoc. remnant	Assoc. High stress	Rock passes	Large chamber	Tunnel & X-cuts	Geology	General
Klerksdorp	5	X	X		X	X	X	X	XXX	Weak footwall Fault/dyke intersect	High ⇔ stress Plastic deformation Tunnel rehab.
Far West Rand	5	X	X	X	X	X	X		X	Greenbar breakout Weak Tuff in h/w	Haulage layout wrt pillars & geology Small faults/dykes?
Central Rand	4	X	X			X			X		Connecting haulages
Orange Free State	5	X	X							Sills cause problems Shale h/w - breakout Fault/dyke intersect	Remnants on dykes! FOG problem
Evander	Small									h/w cross bedding - very low cohesion	

The principal findings were:

- A trend of increasing depth of mining with problems related to regional support, high stope width areas, protection of connecting haulages and geological factors. Seismicity associated with pillars, faults and dykes is an area of concern particularly in high stress areas.

- High percentage production from special areas with associated problems such as bursting, access and layout with respect to other mining and geology.

- Deep level scattered mining and problems with the protection of advance haulages and negotiation of geological features.

2.2 Literature review - summary of major findings

Cook and Salamon (1966) found that as mining extends to greater depths, the frequency and severity of rockbursting is likely to increase, and that radical changes such as the introduction of stabilizing pillars are required to moderate this hazard. They further point out that such mooted radical changes need only apply to mines that are unable to achieve adequate improvements using current support. As mining at ultra-depth is considered, both "radical alternatives" and the improved use of current support methods need to be examined and evaluated.

Salamon (1985) suggests that there are two essential ingredients to reduce unstable rockmass behaviour at depth - firstly, to limit the change in stress and energy due to mining by restricting volumetric closure and secondly, to design layouts in the vicinity of geological features to reduce the large rockburst potential. They indicate that pillars and backfill provide the most promising ways of achieving these objectives, and that these coupled with current improvements in local support would lead to greater safety.

Wagner (1987) states that gold mines are, and will increasingly be working where stresses exceed the strength of the rockmass. The challenge for rock mechanics is to lay out mines and sequence excavations so as to obtain a most favourable fracture zone from a support point of view.

It is clear that the future of the South African gold mining industry depends to a large extent on finding safe, feasible and economically viable techniques for mining at ultra-depth.

Mining at ultra-depth will exacerbate current deep-level mining problems which include seismicity and rockbursting, rapid closure rates, high face stresses and fractured rock, pillar and abutment failure and difficulty in negotiating faults and dykes. Mine layouts should be designed to minimise these problems. Work on procedures for negotiating geological features is underway. Current local support including rapid yield hydraulic props (RYHP), headboards and backfill should prove adequate for increased depths provided standards for use are strictly adhered to. Very rapid closure rates argue in favour of backfill, although this may make the use of hydraulic props more difficult.

Support in the face/gully area and problems related to temporary face support and cleaning need further work.

Scattered mining at depth is required in highly faulted areas and where grades are highly variable. Such conditions exist on some of the new ultra-deep mines being planned. Significant changes to adapt current scattered mining layouts for such high stress conditions need to be examined, such as protection of advanced haulages. Experience at Elandsrand Gold Mine shows that scattered mining can work well at deeper levels.

Good regional support is essential for ultra-deep mining to reduce the seismic potential and to reduce face stresses, and remains a high priority area for further research. Stabilizing pillars are working well on a number of mines, and in such cases should translate well to deeper levels. A better understanding is required of the geological and other conditions that lead to violent pillar failure and work on this problem continues. In the longer term, alternatives to pillars should be investigated as economics may require 100 percent extraction. Suitably designed backfill or pillar/fill combinations, tailored to match a particular mining configuration may replace or supplement stabilizing pillars. The use of concrete ribs and crush pillars hold promise, and should be investigated further.

Pre-extraction of the shaft reef area is indicated for all deep/ultra-deep-level mines. Support alternatives include stabilizing pillars, satellite pillars, crush pillars, backfill and combinations of these. Alternatives and details relating to shafts have been well covered by McKinnon (1990). The long-term stability of shaft associated excavations, including large chambers, rock passes, haulages and the shaft itself, is of concern as stresses will approach virgin stress. Further work should address this problem as well as the location, proximity to on-reef pillars and support of these vital structures.

Haulages and off-reef development are another priority area and should, wherever possible, be developed in de-stressed ground, where virgin stress levels are an upper limit for stress. Support should be designed to suit local ground conditions, but must offer aerial coverage, must be able to yield, and maintain a support resistance of at least 60 kN/m^2. Layouts should be designed to avoid unfavourable proximity of mining to pillars, abutments, faults and dykes. Traversing beneath pillars, or through geological features should be minimised, should be close to normal to the feature if mining does intersect such features, and supported appropriately. Development ends should be well supported. Work should be carried out on improved layouts and on using follow-on development for deep-level scattered mining. Methods of developing and protecting advance development and long-term connecting haulages in areas of high stress should also receive attention. There seems to be no doubt that tunnels at depth, and in advance of mining will be required, either for cross-connections or for pre-exploring the orebody.

Work is currently being carried out on the application of pre-conditioning to mining highly stressed reef areas. This could be applied in order to pre-fracturing stabilizing pillars to reduce violent

foundation damage. Experience in Canada suggests that preconditioning ahead of deep-level haulages approaching highly stressed ground or geological features can reduce strain bursting at the development face.

Mine layouts and sequences should be designed to minimise the formation of remnants, and where remnants are formed, care should be taken to make their shape, size and location with respect to mining, geology and off-reef development as favourable as possible for later extraction. In remnant extraction the history of remnants in the area should be considered, and generally rockburst precautions taken. Principles for such mining have been well described in the Guide (1988). Further work on developing seismic indicators of the burst potential of a remnant seems warranted.

2.3 Industry workshop - topics, discussion & findings

At a high level industry workshop held early in 1994, a number of topics categorised under regional support, layouts, off reef excavations and local support were discussed with a view to setting future direction for work in this project. This section summarises discussion topics of relevance, with a complete report given in Appendix 3.

Regional support

Good regional support is essential for deep/ultra-deep level mining as it reduces the stress at the face and the seismic potential. Problems with pillar stability motivate further work in this area.

Crush pillars with a width to height ratio of between two and four will be fractured throughout, and in the post-failure range can provide very stiff support right at the face, which will limit ERR, face stress and closure. Their advantage over stabilizing pillars is that foundation failure is eliminated and extraction percentage increased. The high initial stiffness should provide more effective local support than backfill alone. Combinations of backfill and crush pillars should be considered.

Stabilizing pillar designs should be modified for improved effectiveness as a regional support element with or without backfill such that failure is reduced, seismicity and seismic damage minimised and extraction percentage maximised. This includes diverse alternatives: preconditioning of stabilizing pillars as they are cut or designing pillars to fail stably at a distance from the face in order to reduce unstable failure and foundation failure, and possibly enable secondary extraction; two stage mining with large pillars and concrete ribs followed by complete or partial pillar extraction; replacement of stabilizing pillars with concrete pillars and backfill; grid pillar variations as an alternative to scattered mining in areas of highly variable grade.

Layouts to minimise adverse seismicity.

Current trends of increasing seismicity with increased mining depth are cause for concern in several areas, including worker safety and the costs associated with rehabilitation of seismic related damage.

Most of the deep/ultra deep level mines have many faults and dykes which are seismically active. As depths and stresses increase, seismicity associated with geological structures is expected to increase. How should one best negotiate such features on and off the reef? Not all geological structures are problematic - and the question arises as to how one can identify "safe" geology in advance. Techniques such as 3D reflection seismics can be used to locate such features more accurately without advance development. Faults with throws >25m can be identified and located from the surface. Work is indicated to improve layouts to reduce this hazard. e.g. Mine away from an identified hazard. Research is currently being carried out to improve bracket pillar design and the identification of hazardous structures.

A number of mines particularly in Klerksdorp and OFS experience difficulty in mining remnants or isolated blocks of ground adjacent to the intersection of a fault and a dyke at deeper levels. Approaching longwalls form long thin remnants having high stress, with associated deteriorating mining conditions, and concentrations of seismicity in face areas. It is clear that remnant bursting is a problem over most mining districts and mines. Some work has been done over the years to relate such bursting to the position, size, shape, stress, direction & rate of mining, with mixed success. Research is required to gain an improved understanding of what allows one remnant to be mined without difficulty, while a nearby remnant in seemingly similar conditions causes considerable problems. i.e. What are the controlling factors - seismic or other? Relatively low accident statistics related to remnants indicates that the special area support applied is generally suitable.

Off-reef excavations.

The safety of workers while maintaining mining operations depends on the long term stability of a number of off-reef excavations including: the shaft complex, rock passes, pump & hoist chambers, haulages and cross cuts. Despite the fact that many of these are protected from the immediate effects of stress by suitable mining layouts, many are damaged through secondary stress regeneration or by seismicity. As mining depths increase, increased stress levels will occur accompanied by increased seismicity, making off-reef structures more susceptible to damage.

At ultra-depth large excavations can no longer be protected by the shaft pillar as pre-extraction of the reef area is essential. Initially these will be de-stressed, and will be subject to increasing stresses which may eventually approach virgin stress levels. (At 4000 m depth this may exceed 100 MPa.) Support needs to be designed to accommodate such stress increases. Care needs to be exercised in placing satellite pillars, stabilizing pillars or crush pillars if they are used. It is possible to mine selected reef areas at a higher stoping width to protect important long-term excavations including the shaft itself from the full increase in stress levels. Several mines at depth report severe damage to rock-pass systems, with damage evident even where the shaft reef area has been pre-extracted and with limited mining. Scattered mining will have to be used at depth in cases of very faulted, geologically complex ground, and where average grades don't warrant complete extraction. Of concern here is the development of suitable layouts for follow-on or on-reef haulages for use with scattered mining, as advance development is likely to be severely damaged and hazardous unless

sited far in the footwall. This may still be difficult to support and may bring practical mining difficulties.

Despite the fact that haulages are sited in destressed ground in longwall mining, improvements in haulage layout may be possible and offer advantages. Work is required to design and locate haulages for reef specific environments. If haulages are too close to the reef, they are in heavily fractured ground, while if they are too far below the reef they may be influenced by abutment stress or cause practical difficulties being too far behind the face. Questions such as: how far should haulages be from stabilizing pillars to avoid damage?, how should faults and dykes be negotiated? and how should these be supported in such areas? need to be addressed.

There may be advantages from both an economic as well as a safety viewpoint to modify mining methods and layouts to minimise the amount of off-reef development. e.g. Have more on-reef access, though this may have problems of long term stability in areas with hazardous geological structures.

Several authors have motivated the shaping of haulages in high stress/weak rock areas to accommodate local jointing as well as to assume a more stable shape from a stress concentration point of view. Elliptical, "T" shapes and ledging the sidewall can be used to move stress concentrations further from the edge of the tunnel. Modelling and experience indicate benefits in this approach, however details of design geometry, support and stability under dynamic load need to be addressed. The integration of such a shaping or ledging so that it is concurrent with primary haulage development is a practical consideration which warrants further work.

Local support.

Local support requirements are generally well defined, and many suitable support elements are available to satisfy each application. Local support remains a high priority because of the concentration of workers in the stope face area and because most rockburst/rockfall related accidents occur in this area. Several other problem areas as well as promising support alternatives have been identified and are set out below.

Is it possible to make changes to the mining method or layout that would reduce the workforce required in identified dangerous areas such as the stope face, the gully intersections and the gully/face area? Water jet, vacuum cleaning and diamond-wire cutting are such examples.

As mining depths increase, so too do closure rates, which may be as high as 100 mm per day at around 4000 m depth. Such rapid closure rates quickly reduce the amount of energy rapid yield hydraulic props (RYHP) and most stope support can absorb under dynamic load. ERR and economic considerations demand that the stope width be kept to a minimum compounding the problem. Several mines report damage to props and units being "locked in" by rapid closures at current depths. Such rapid closure reduces the effectiveness of most stope support with the

exception of backfill. Can changes to the mining system, layout, support strategy or support units themselves minimise the negative effects of such closure rates, or use them to advantage?

The effectiveness of backfill initially as a local support and ultimately for regional stability is dependent on many factors such as quality, density, fill/face distance, closure rate... as well as fill height in the stope and slumping/shrinkage. It may be possible to address the fill height in the stope and slumping/shrinkage by pumping in a suitable high stress cementicious foam (1 MPa) between the fill and the hangingwall, or effectively pre-stressing the fill in some other way.

"Spray on" supports have a very high shear strength and may assist in stabilizing the hangingwall, providing improved aerial coverage in the face area. Could this be applied to the face itself in areas prone to face bursting? Short end anchored bolts are being used to supplement face support to good effect on some mines and should be investigated with possible application in deep level & high stress areas.

2.4 Indicated direction

As a result of the findings of the literature review, questionnaire and workshop, the remainder of the highly stressed areas project was focused on the following priority areas:
- to develop new and improved layouts and regional mining strategies to satisfy indicated mining and geotechnical conditions.
- to study remnant stability with a view to reducing remnant associated problems.
- develop improved seismic techniques.

3. ULTRA-DEEP MINING

Despite a significant amount of mining currently taking place at depths exceeding 3000m with reasonable safety, there are a several counter examples and several trends causing concern. These being the incidence of foundation failure and the marked decrease in extraction percentages.

3.1 Ultra-deep mining conditions

A trend of increasing fatality and accident rates with increased depth has been observed previously (Gay et al, 1995), though this is not borne out by more recent statistics - as Roberts (1995) shows no increase with depth! In order to design improved mining methods for increasing depth a better understanding of mining conditions anticipated is required. Due to the unavailability of measurements, this information has to be extrapolated from current depths with concurrent numerical modelling.

Very rapid stope face area closure rates reduce the effectiveness of face support including hydraulic props. Figure 3.1 shows stope closure profiles vs distance from the face for depths ranging from 3000 to 5000m (Young's modulus = 50 GPa, 5m grid size).
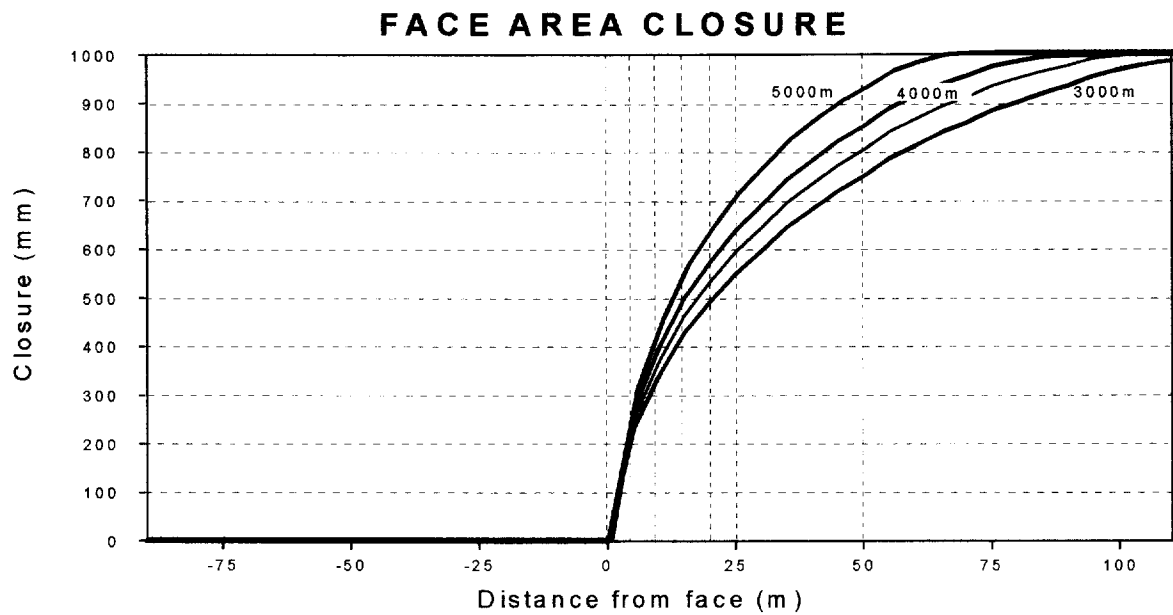

Figure 3.1 Profiles of stope area closure.

Virgin stress levels may exceed 100 MPa. Virgin stresses and back area stress regeneration may in some cases exceed the strength of certain strata. Very high mining induced stresses ahead of the face are indicated as shown in Figure 3.2. While these are elastic stress profiles and face area fracturing will certainly redistribute this stress over a greater area, it is believed that this fractured rock may be very highly stressed, far more so than previously thought.
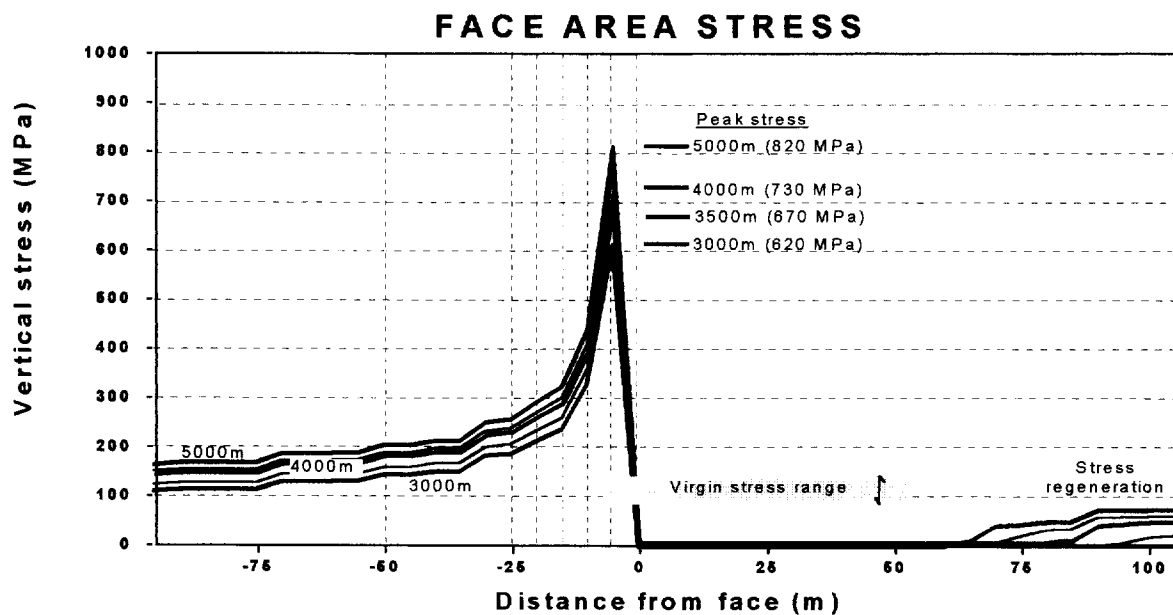
Figure 3.2 Profiles of stope area stress ahead of the face.

The energy release rate (ERR) as a measure of both mining hazard and of seismicity is shown in figure 3.3.
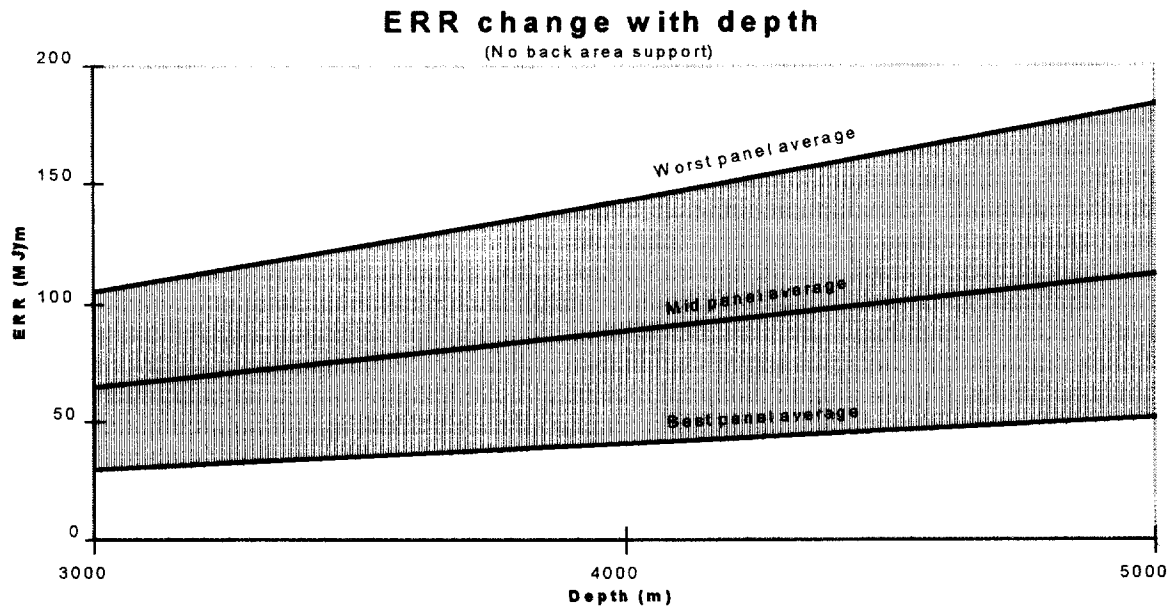
Figure 3.3 Range of ERR panel averages with depth.

The deep-level mining conditions listed in the Chamber of Mines (COM) Industry Guide (1988) apply and will be exacerbated as depths increase to ultra-deep-levels. The primary areas of concern are listed below:

•The trend of increasing accident and fatality rates with increasing depths.

•High stress and ERR

  - high stress levels and high ERR gives rise to highly fractured rock,

  - stabilizing pillar failure, punching or foundation failure,

  - gullies adjacent to abutments or pillars are difficult to support,

  - scattered mining difficulties such as high abutment stress, advance development and remnants,

  - tunnels, rock passes and off-reef excavations subject to high ambient stress and stress change make support more difficult.

•Seismicity and rockbursting increase

  - seismicity which is often associated with geological discontinuities,

  - difficulty in negotiating faults and dykes,

•High closure rate

  - rapid closure rates reduce the effectiveness of local support, with the exception of backfill,

  - very rapid stope closure gives rise to rapid, high stress regeneration in the back area,

3.2 Principles for Mine Layout Design

There are four major requirements for consideration in mine layout design for new mining areas:
- knowledge of grade distribution (usually known to some extent),
- geological structure (partly known, and techniques exist to get much of the required information),
- *in situ* state of stress (usually unknown - few measurements),
- engineering properties of the rockmass (sparsely known - averaged and extrapolated).

The guide lists a number of strategies for mining at deep-levels, and while these may not necessarily translate to the ultra-deep conditions, they at least provide a starting point for further work.
- mining sequences should be modified to reduce average ERR and stress levels and minimise deleterious effects of remnants (longwall or scattered),
- regional support (pillars or backfill) should be used to reduce rockburst hazard,
- procedures for negotiating geological features (bracket pillars) need to be devised,
- longwall mining with follow-on haulages preferred,
- local support to cope with highly fractured rock, rapid closure rates and seismic loading,
- leads and lags kept to a minimum in high stress areas,
- keep gully headings to a practical minimum,
- pillars may be required in very high stress/deep-level scattered mining layouts,
- gully support should include yielding tendons and lacing in problem areas.

While some of this information is available, much more detail is required. Available and additional data is represented in a framework format in which additional data can be added as available.

3.3 Geotechnical environment at ultra-depth

One of the requirements for mine layout design is a better understanding of the geotechnical conditions associated with reefs likely to be mined at ultra-depth. Considerable information has been gathered and collated in a database which includes:
Tabulated projected future production figures by reef.
For each reef details are presented on:
- reef properties & geometry including both lateral and vertical variations,.
- frequency and characteristics of bedding planes and lithological boundaries,
- 100 m into hangingwall & footwall - rock types and available properties are listed,
- compositional and textural characteristics of faults, dykes and joints.

A paper on this work is currently being prepared, and is given in Appendix 6.

Depth of mining of the aurifereous Witwatersrand deposits is continuously increasing. Some mines are already mining at depths exceeding 3500m (see Figure 3.4). Production costs are similarly increasing, with health and safety aspects simultaneously gaining in importance. Novel approaches, considering mining strategies, layouts and support systems have to be adapted, in order to mine deep orebodies safely and efficiently.
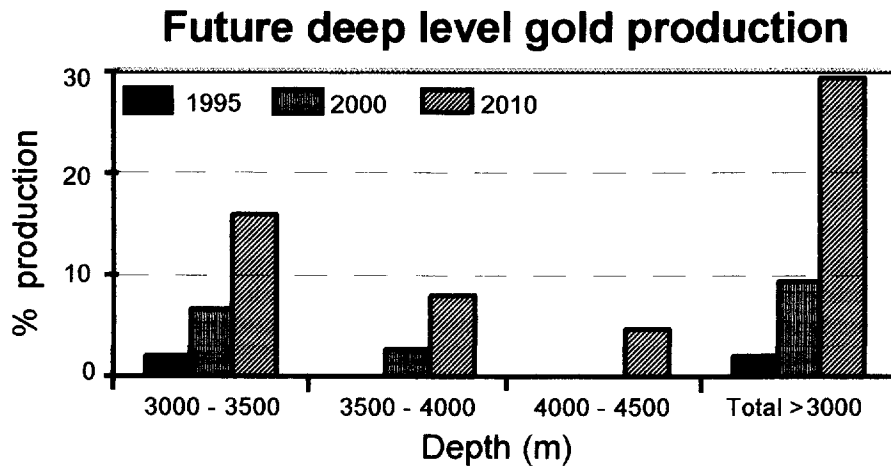
Future deep level gold production

Figure 3.4   Predicted gold production at depths > 3000 m. (After Schweitzer & Johnson 1995).

Deformation mechanisms associated with Witwatersrand orebodies are complex. The importance of geological features is unquestionable, although their impact is obscured by mining parameters. The geological features to be considered are grouped into two categories, i.e. primary and secondary geological features; both are of rock engineering importance and contribute to the definition of geotechnical areas.

Primary geological features referring to the rock type, are largely defined by texture and composition, which is also reflected in varying rock engineering properties. These vary vertically and laterally, i.e. in time and space. These variations are observed in the orebody itself, and its hanging- and footwall rocks. Primary geological features also include the frequency and mineralogical characteristics of sedimentary structures, such as the various kinds of bedding planes and lithological boundaries. In most instances these are reef parallel. The third primary feature to be considered is reef geometry.

Secondary geological features are faults, dykes and joints. These have, to date, received most attention from the rock engineers. Compositional and textural characteristics of these discontinuities are also deemed important.

Primary and secondary geological features impact, especially at great depth, on the rockmass behaviour, expressed as closure rate, seismicity, and mining induced extension and shear fracturing. They play an important role in identifying the appropriate mining strategy, layout and support. Geological features can be predicted into deep unmined areas though the success of such extrapolation has yet to be proven. The use of these predictions in conjunction with computer

simulation of the rockmass at ultra-depth aims at the identification and recommendation of the safest and most efficient extraction of the orebody.

The majority of the orebodies presently being mined will, potentially, be extracted from ultra-depth. The majority of these, in turn, are situated in complex geological environments.

About 20 mines and project areas that are mining, or will potentially mine, at great depth have been identified. Several operating mines are reaching these depths at present: Western Deep Levels (AAC), ERPM (RM), Kloof (GF), West & East Driefontein (GF), Leeudoorn (GF). Ultra-deep mining in several other areas has been proposed, or is being developed: Target (AV), Sun (AV), Strathmore (Genmin), South Deeps (JCI), Moab or East Vaal (AAC). In addition, exploration has identified other deep level ore reserves which could be developed in the longer term (Potch. gap for example). These projects represent the interests of all the major mining houses and cover all current mining districts excluding Evander.

The VCR, Carbon Leader, Main Reef, reefs of the Elsburg and Kimberley successions, Vaal Reef, and the Basal Reef are the major targets. Some of the important rock engineering characteristics of these reefs are summarised in Table 3.1. Hangingwall and footwall stratigraphic information and wherever available, rock engineering properties have been compiled for each of these reefs.

OREBODY	REGION	FOOTWALL	HANGINGWALL	CHANNEL WIDTH	GRADE	DIP (deg.)	COMMENTS
VCR/ (Kruidfontein)	Carletonville Klerksdorp Bothaville	Highly variable Shale-Conglomerate	Westonaria Formation (0-40 m) Alberton Porphyry Formation (< 500 m)	0-2.00 m	Erratic	15 - 35	Rolls Pillars Bedding parallel faulting
Upper Elsburg/ Massives	West Rand	Quartzite	Quartzite	1.20 - 1.80 m > 1.80 m	Erratic	0 - 15	Pillar spacing
Elsburg-UEIA BP,A	West Rand	Quartzite	Shales above grey hangingwall quartzite	1.20 - 1.80 m > 1.80 m	Erratic	0 - 15	Pillar spacing
Kimberly	Bothaville West Rand Evander	"K8" Shale Quartzite	±Argillaceous partings	1.20 - 1.80 m	Erratic	15 - 45	Channels support on shale
B	Bothaville	Strongly Argillaceous	Quartzite	0.10 - 2.00 m	Even-erratic	15 - 45	Channels < 200 m wide
Styn/ Basal/Vaal	Klerksdorp O F S	Quartzite	Argillaceous Quartzite Shale	(< 1.20) 1.20 - 1.80 m	± Even	15 - 30 (OFS) 15 (Klerks.)	Flat channels Closure
South/ Composite	Central Rand	Quartzite (±Shale)	Quartzite	1.20 - 1.80 m	± Even	30 - 45	
Carbon Leader/ Main	Carletonville	Quartzite	Quartzite (Bedding planes) Shale (1-2 m thick)	1.20 m	± Even	15 - 30	Green Bar

Table 3.1   Table summarising orebody information with principal hangingwall and footwall characteristics.

Evaluation of the data reveals that a variety of rock types, having distinct rock engineering properties, are located in close proximity to the   excavations.   Partings and dykes are also prominent.

Pronounced lithological variations are observed beneath and above most of the reef horizons under consideration. The four major footwall and hangingwall lithologies considered are shales, quartzites, argillaceous quartzites, and conglomerates. Two additional hangingwall lithologies overly the VCR. These are informally termed the soft and hard lava, which correspond with the official terms Westonaria formation and Alberton porphyry formation respectively.

The majority of reefs considered are located in a complex geological environment, and are also characterised by variable associations of footwall/hangingwall lithologies. Secondary geological features are also prominent. Different geological environments will be expressed by different mining conditions at ultra-depth and will impact on the mining strategy. The compiled information will be used as input for computer modelling.
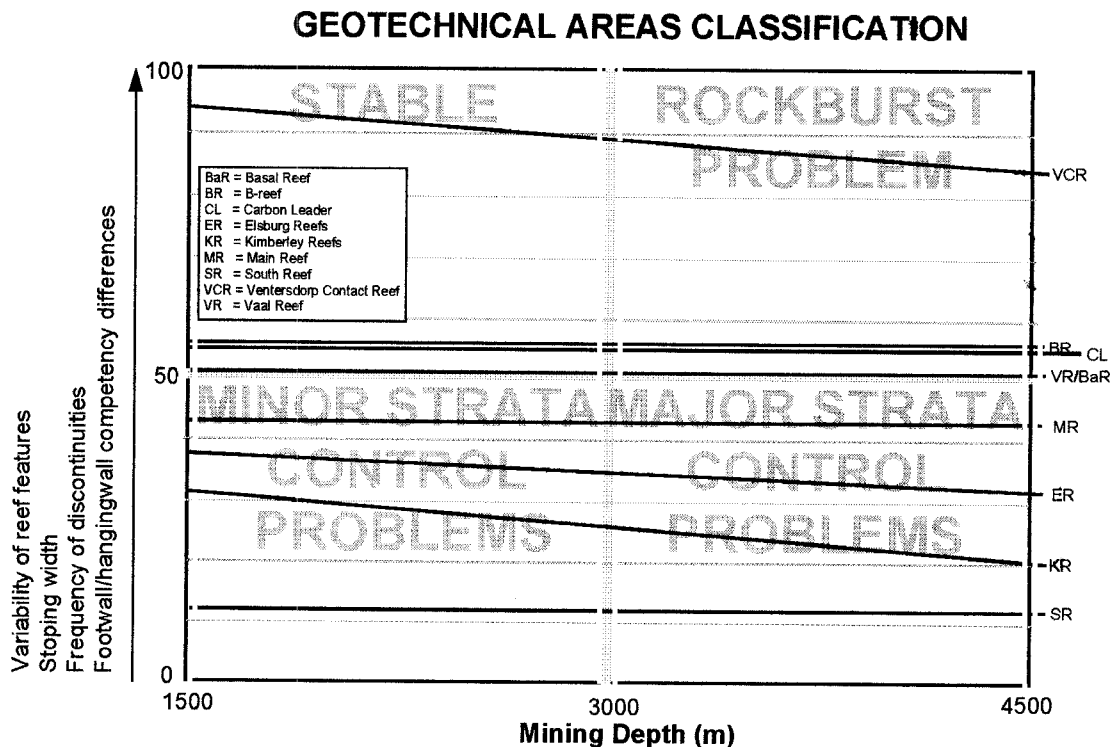
Figure 3.5 Geotechnical areas classification (After Schweitzer & Johnson 1995).

Geological/geotechnical factors have a major influence on the type of mining, the mine layout and the support requirements to exploit such deep level reserves. It is felt that in many cases current mining methods cannot simply be extended to greater depths without compromising safety, and will require significant modifications or completely new mine design ideas. Such new or modified mining methods need to be "tuned" to the prevailing geological conditions. To this end a broad geotechnical classification is required in which as many as possible of the factors listed above are to be tabled. Figure 3.5 shows a classification for different reefs and depths. The vertical axis is a weighted average of footwall/hangingwall competency difference (30%), frequency of discontinuity (40%), stoping width (20%) and variability of reef properties (10%). This draft classification will be described in more detail in a paper currently being drafted. It is anticipated that details of the classification will change with mining area, that additional information will be added and weightings varied as more information is obtained.

3.4 Assessment of mining methods, layouts and alternatives

In this section comparative rock engineering assessments are presented of:

- mining methods commonly used at depth,
- modifications to above methods,
- new mining methods.

As far as possible, models used have been set up to make the comparisons as fair as possible. A Young's modulus of 50 GPa, a stoping width of 1m, rock density of 2700 kg/m^3 and k-ratio of 0.5 have been used throughout. The primary factor used in the comparison is energy release rate (ERR), while stope area closure, face stress and pillar stress are also used. ERR is an accepted measure of mining condition and seismic risk. Face area stress relates to ease of mining and of face burst potential. Closure has a bearing on the energy absorption effect of stope support elements. Pillar stress is indicative of the failure potential of the pillar or surrounding rock.

Current methods

Most current deep level mining is carried out using a longwall configuration with stabilizing pillars of at least 40m width and at planned extractions of 80 to 85%. While this method performs relatively well at depths exceeding 3000m at present at a number of mines, there are significant problems with pillar stability and associated seismicity in some areas.

Current methods modelled are:

- 40m stabilizing pillars at 85% extraction,
- 60m stabilizing pillars at 80% extraction,
- 75% stope filling with backfill only right to the face (a=8.0, b=0.3, fill width=75%)
- 40m stabilizing pillars at 85% extraction with 75% stope filling with backfill to the face.

CURRENT METHODS - ENERGY RELEASE RATE
(Mid panel average)
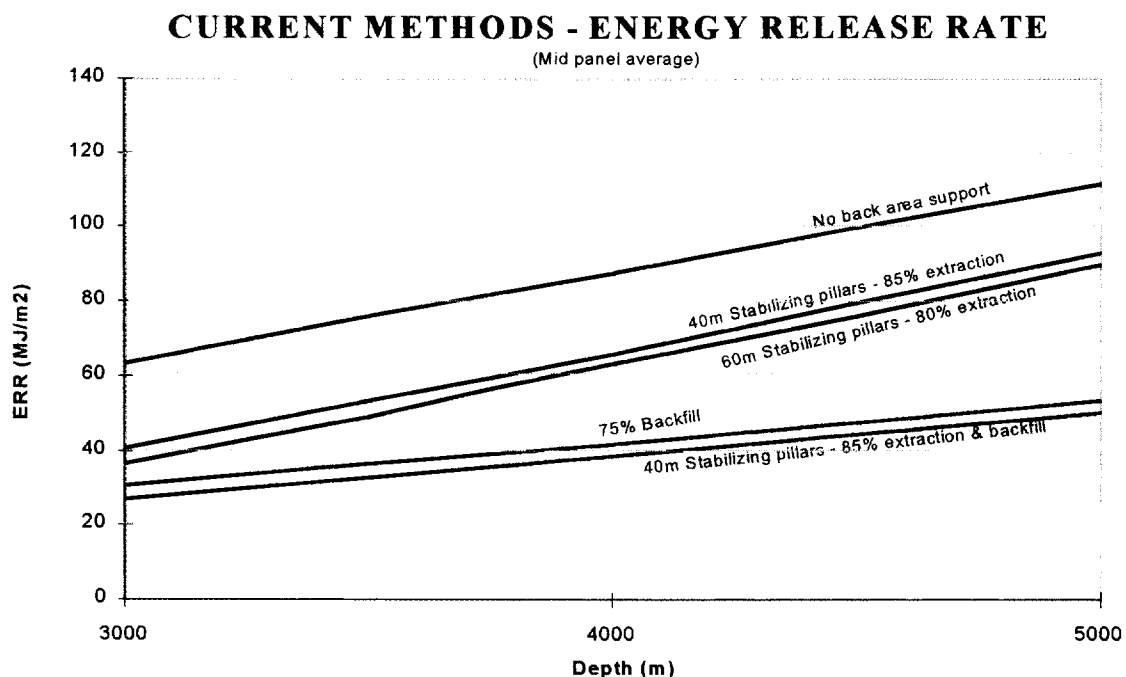
Figure 3.6   ERR (mid panel) comparison for current deep level mining methods.

Figure 3.6 shows the mid panel average ERR for four current methods and includes the case of no back area support as a base case for depths from 3000 to 5000m.

One can see that both stabilizing pillar geometries without backfill increase from about 40 MJ/m^2 at 3000 m and in general do not appear suitable for mining to greater depths. Both backfilled cases are significantly better, having acceptable ERR's to depths of almost 4000m.

Similar results are shown for the average ERR for all longwall panels in Figure 3.7

CURRENT METHODS - ENERGY RELEASE RATE
(All panel average)
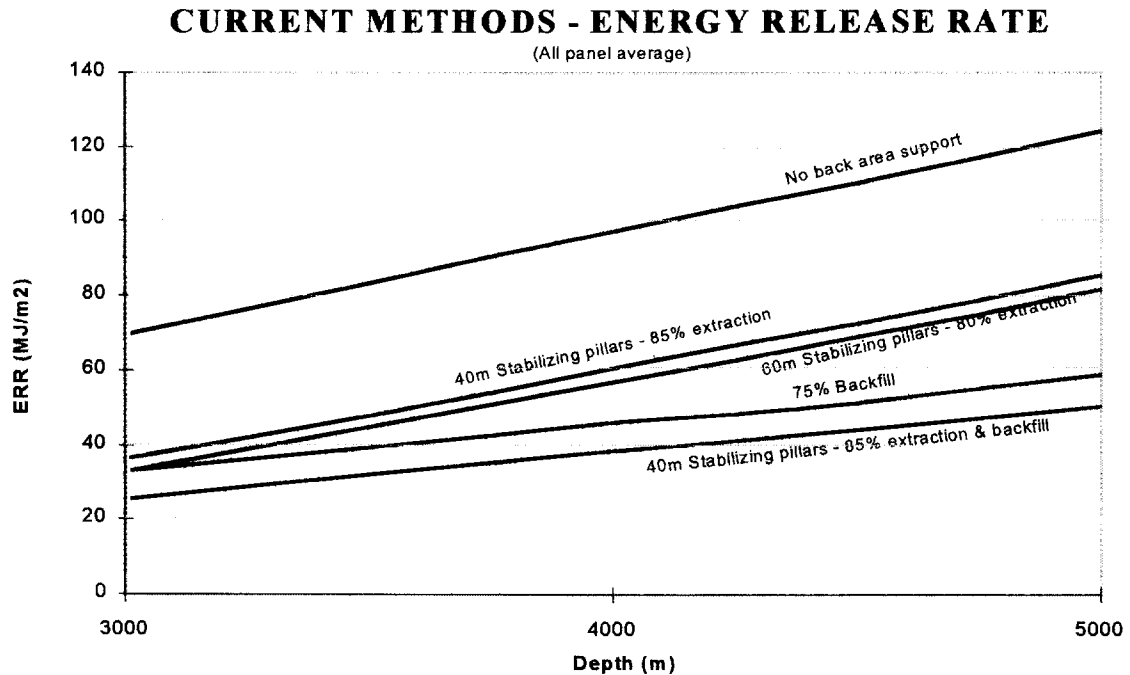
Figure 3.7 ERR (overall average) comparison for current deep level mining methods.

Of significance is the changed slopes of the filled cases, showing improved values and a slower rate of increase. This strongly motivates the use of methods that incorporate backfill in any ultra deep mining method.

Figure 3.8 and 3.9 show comparative curves for stope closure (average for 20m) and face stress (average for 5m) respectively. Again the filled cases are better, though the high values of both are cause for concern. High face stress conditions may be addressed by pre-conditioning, though this will exacerbate the already high stope closures. Rapid stope closure limits the effectiveness of the yielding support that is essential in such mining by decreasing the potential to absorb the kinetic energy of the hangingwall blocks.
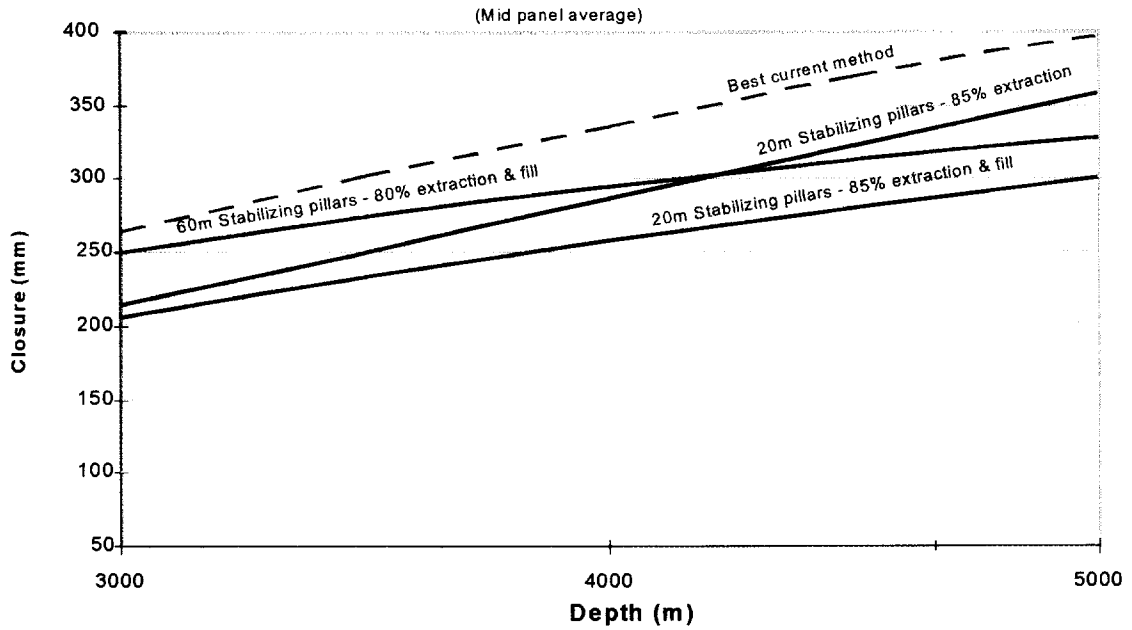
CURRENT METHODS - STOPE AREA CLOSURE
(Mid panel average)
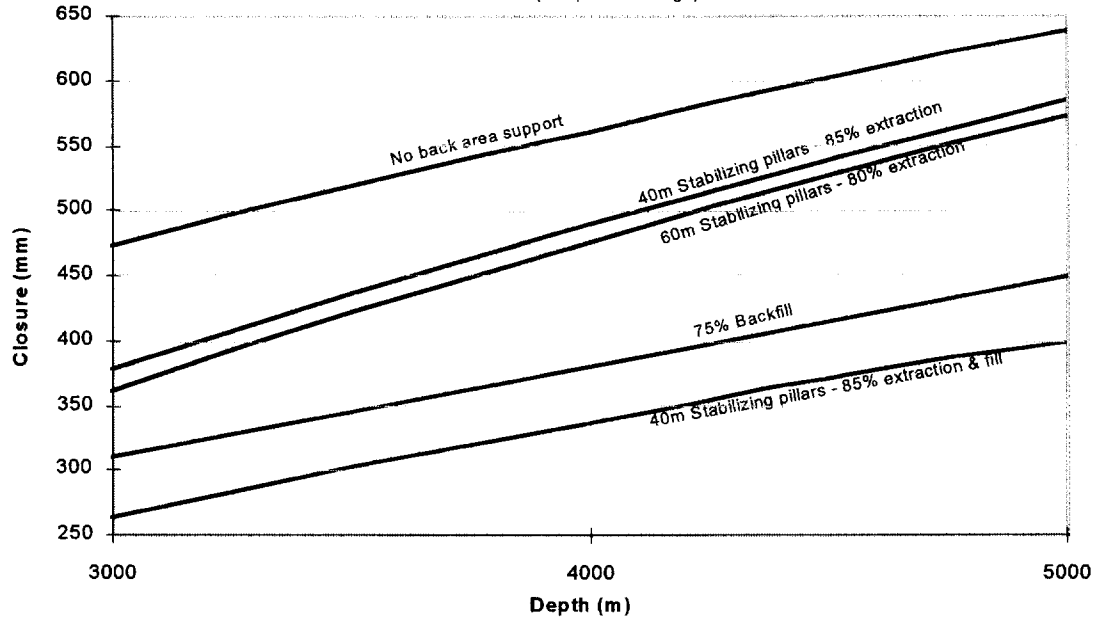
Figure 3.8 Average (20m) stope closure comparison for current deep level mining methods.

CURRENT METHODS - FACE AREA STRESS
(Mid panel average)
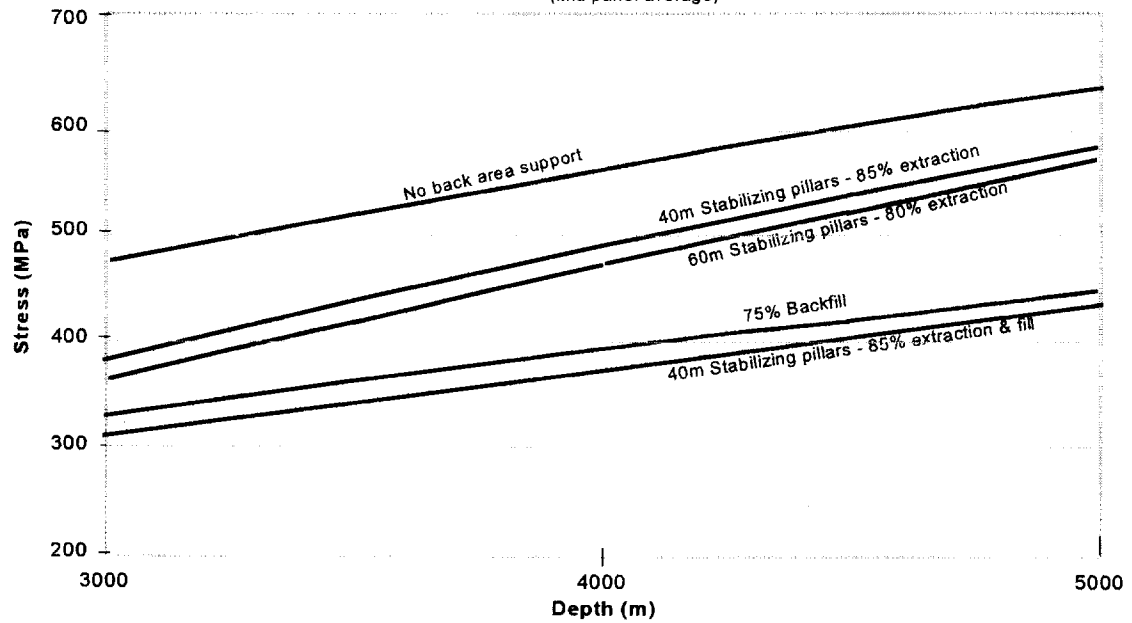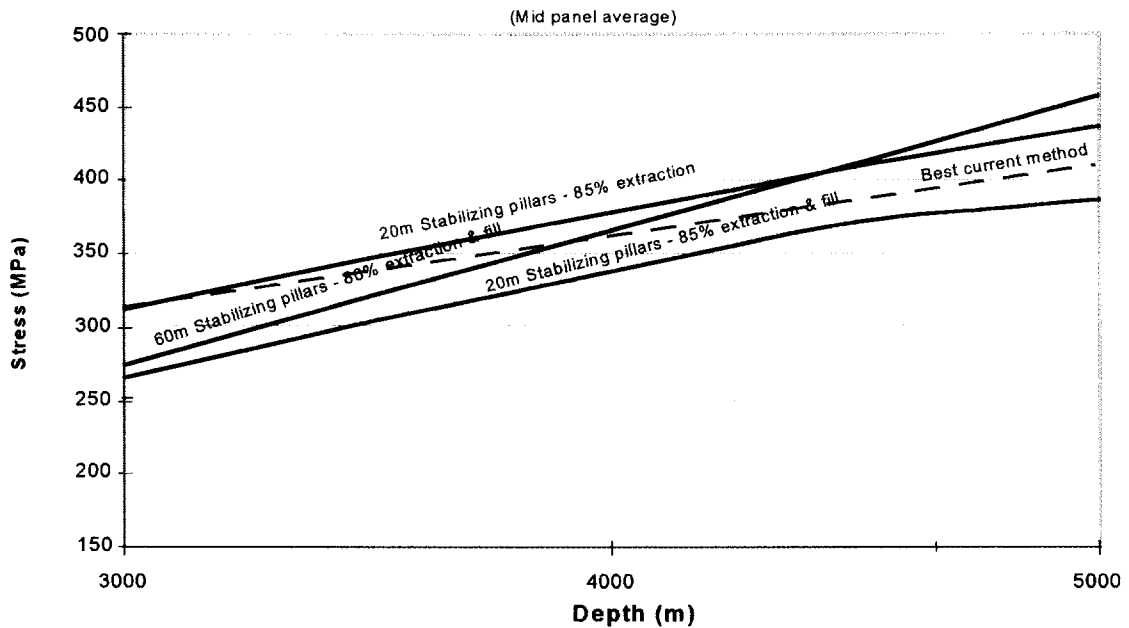
Figure 3.9 Average (5m) Face stress comparison for current deep level mining methods.

Where applicable average pillar stresses for the different methods are plotted in figure 3.10. The beneficial effects of the backfill can again be seen. This would indicate that stabilizing pillars with backfill are a suitable method at depths exceeding 3000m particularly in a "soft" environment (see Figure 3.5).

CURRENT METHODS - PILLAR STRESS
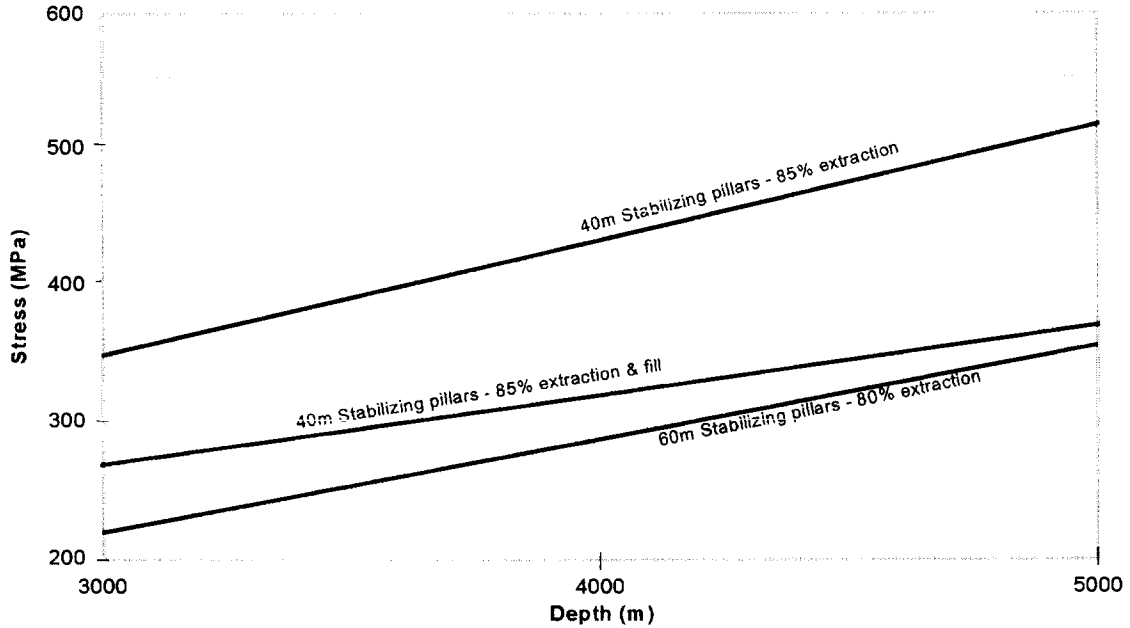
Figure 3.10   Average pillar stress comparison for current deep level mining methods.

The major disadvantages of the use of stabilizing pillars at depth are their failure potential in "hard" environments, inflexibility of position which may correspond with high grade areas, influence of these pillars on nearby haulages and that in practise over 30% of the available ore is effectively sterilised (Vieira, 1995). Economic considerations at increasing depth favour increased extraction, and extraction is decreasing with increased depth.

Modified current methods

The stabilizing pillar method may be changed by reducing the pillar width to 20m.

MODIFIED CURRENT METHODS - ENERGY RELEASE RATE
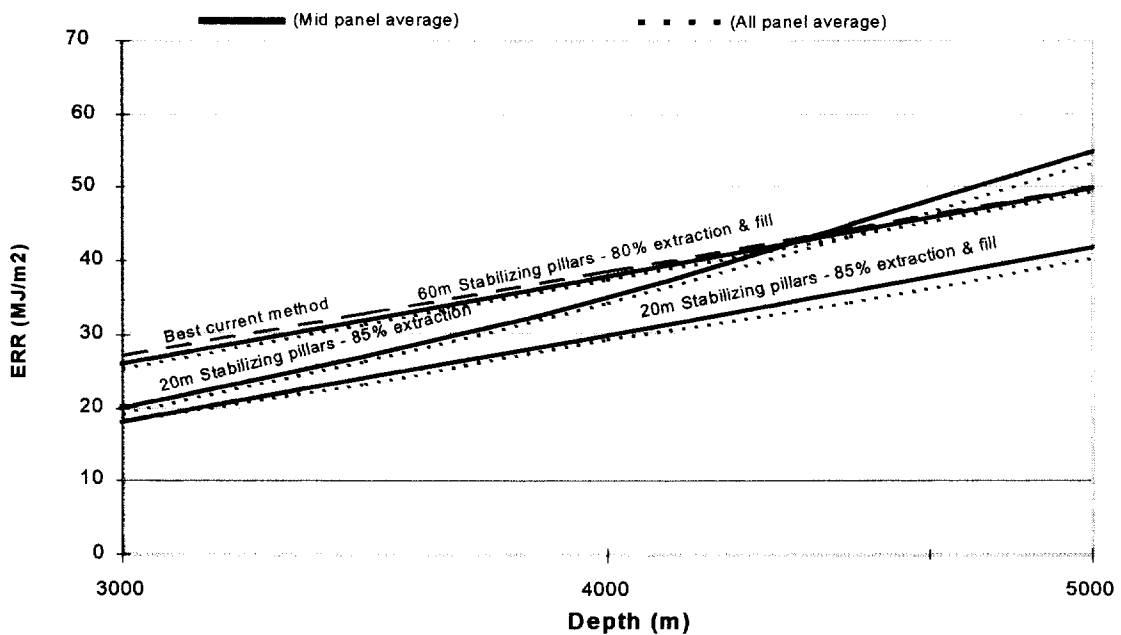
Figure 3.11   ERR comparison for modified current deep level mining methods.

It can be seen in Figure 3.11 that 20 m stabilizing pillars give improved ERR values, even for unfilled case compared to the larger span filled case.

This would indicate that improvements are possible by maintaining 85% extraction, and halving longwall spans.

MODIFIED CURRENT METHODS - STOPE AREA CLOSURE

Figure 3.12   Average (20m) stope closure comparison for modified current deep level mining methods.

MODIFIED CURRENT METHODS - FACE AREA STRESS

Figure 3.13   Average (5m) Face stress comparison for modified current deep level mining methods.

Figures 3.12 and 3.13 above show that 20 m pillars have similar face stresses and substantially improved stope closures compared to current methods.

MODIFIED CURRENT METHODS - PILLAR STRESS
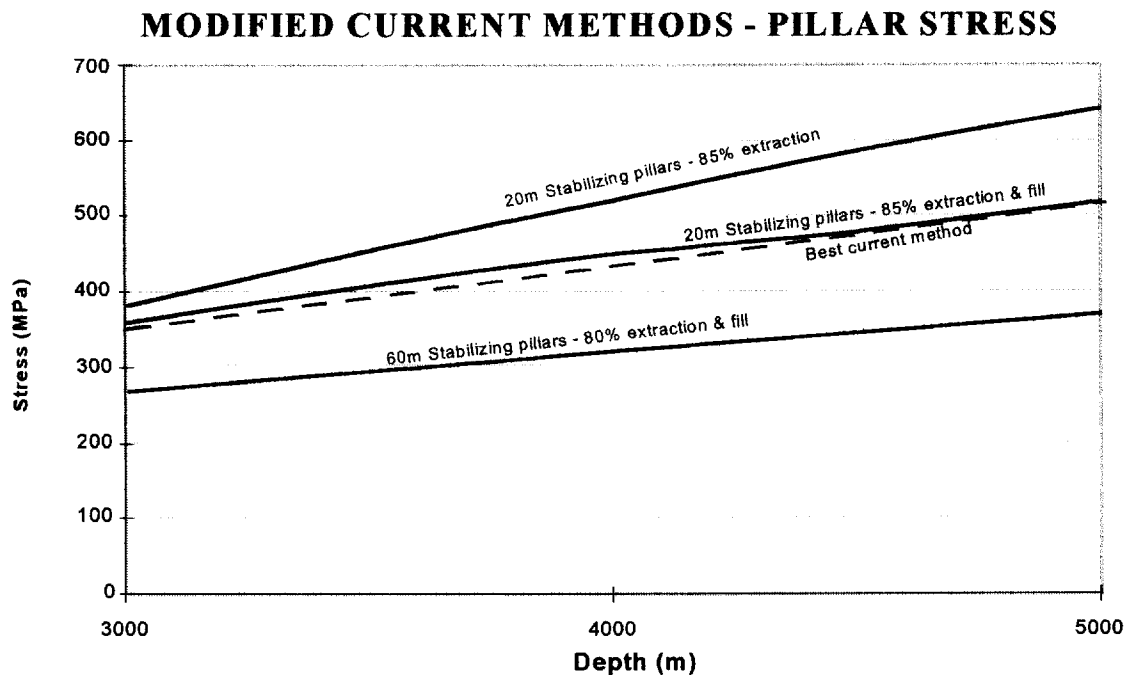
Figure 3.14   Average pillar stress comparison for modified current deep level mining methods.

Average pillar stress shown in Figure 3.14 shows the 60m pillar more stable, and that the unfilled 20 m pillar case has unacceptably high pillar stresses.   The 20 m pillars with fill have similar pillar stresses to the 40m pillar with backfill case. As before, these are suitable for "soft" environments, but would be prone to failure in "hard" cases.

The 20m pillars are preferred to 40m equivalents, having significantly more favourable ERR and stope closure values with similar face and pillar stresses. Despite these indicated improvements, Diering (1987) documents problems with 20m pillars at Western Deep Levels that motivated changing to 40m pillars.

New Methods - Regional assessment

A brief of this project was to propose new mine layouts and methods suitable for application at ultra-depth. Two alternate regional support layouts are proposed, and several more detailed in panel configurations for use with these regional layouts.

The first regional layout proposed is for "hard" environments and makes use of concrete and backfill, and is termed multi-pass mining and is illustrated in Figure 3.15.

Phase 1 of this layout mines 160m wide headings with backfill, placing concrete ribs adjacent to the central abutment of 160 m in width. This provides a low closure environment for the concrete to

cure to optimum strength. Phase 2 of this mining (also using stope filling) is to mine the central 120m keeping this face around 100 m behind the advance faces. This is mined with two 20 m strike pillars adjacent to the concrete. These pillars are then extracted in a third phase, a further distance behind the Phase 2 face yielding 100% extraction. The third phase could be omitted if mining conditions were difficult, though pre-conditioning of the pillar as part of the phase 2 mining may facilitate this mining.
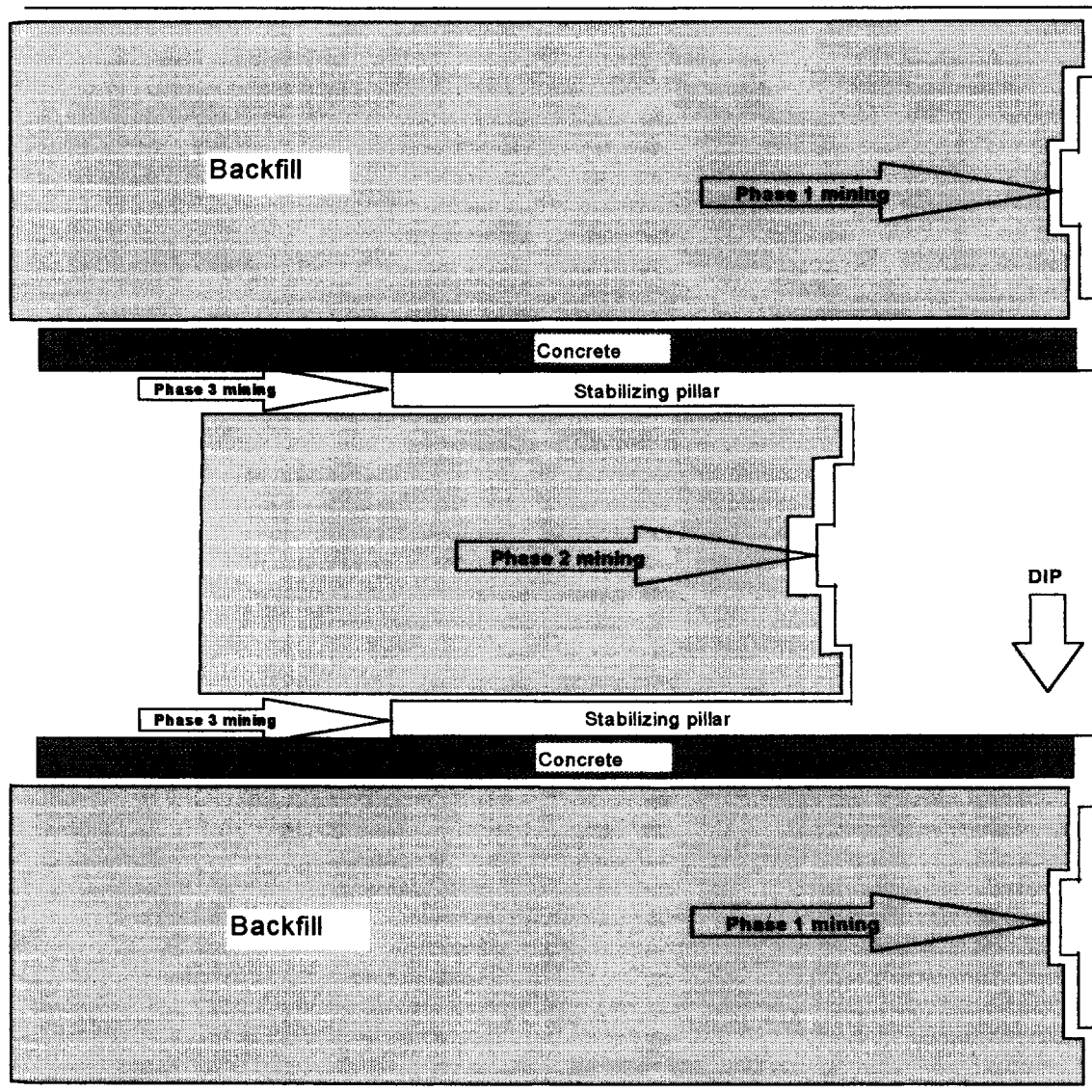
Figure 3.15   Multi-pass method regional layout suited to "hard" deep level environment.

The second new regional layout is a further modification to the 20 m stabilizing pillar layout already described and is advocated for "soft" environments. This is illustrated in Figure 3.16. A concern related to stabilizing pillars is the potential for pillar system failure - i.e. failure of the pillar or surrounding strata. Laboratory work described in section 3.5 illustrates the effect of confinement on pillars, so this method is modified to provide additional confinement to these stabilizing pillars. As pillar failure usually takes place in excess of 100m behind the face, backfill is placed right up to the pillar on the up-dip side of the pillar & behind the dip gully. A cave is induced in the back area on the down dip side of the pillar again behind the dip gully. While comparisons have been made

without the use of extensive stope backfilling, results given above indicate the advantages of such filling.
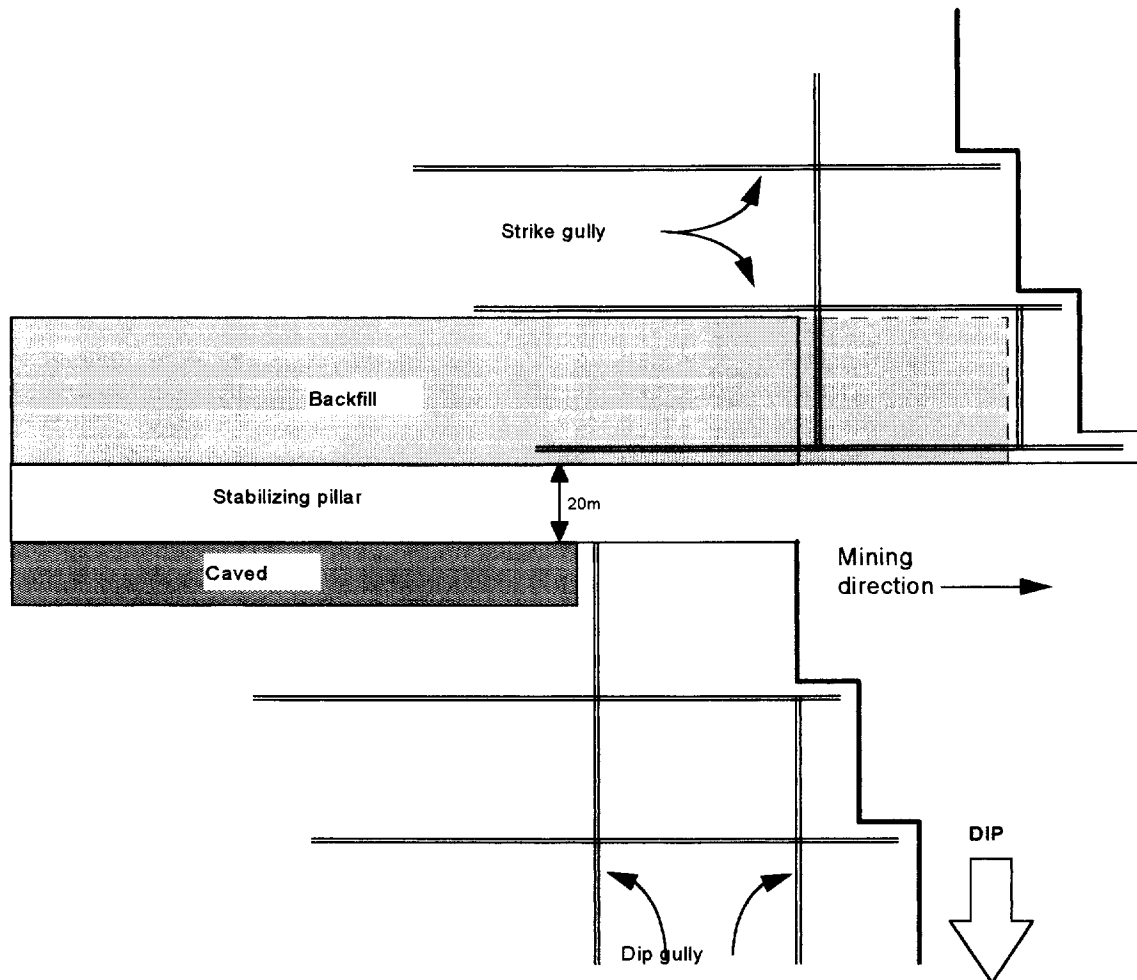
Figure 3.16   Modified stabilizing pillar regional layout suited to "soft" deep level environment.

Both of the above regional layouts should not be too difficult to mine from a practical point of view since they are similar to current longwall configurations.

A third regional layout has been evaluated - the use of bord & pillar mining - adapted from a layout proposed by deFrey (1993), and illustrated in figure 3.17. Initially this concept looked attractive as it provides a very low ERR on the face for a first extraction of 75%. The squat pillars can be mined at reasonable ERR if stiff in-stope support such as concrete is used, and these are not removed too far back from the face.

Major disadvantages have led to this method not being suggested. The practicalities of mining and ventilation are difficult. Far more serious is the burst potential of these squat pillars, even with concrete.
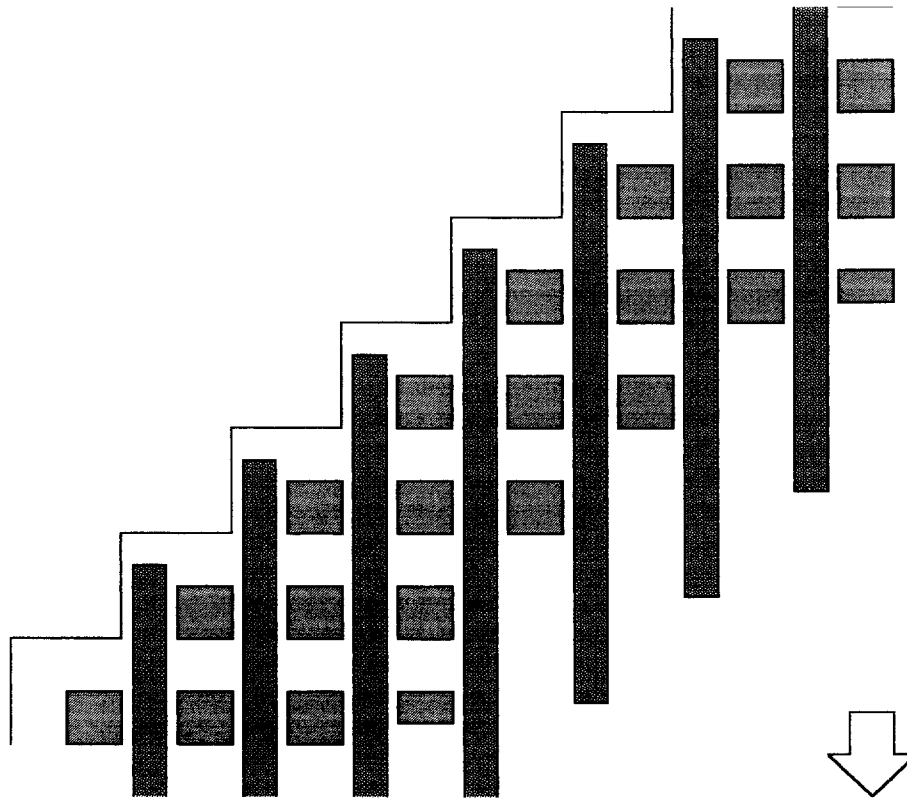
Figure 3.17   Multi-pass bord & pillar regional layout considered.

NEW MINING METHODS - ENERGY RELEASE RATE
(Mid panel average)
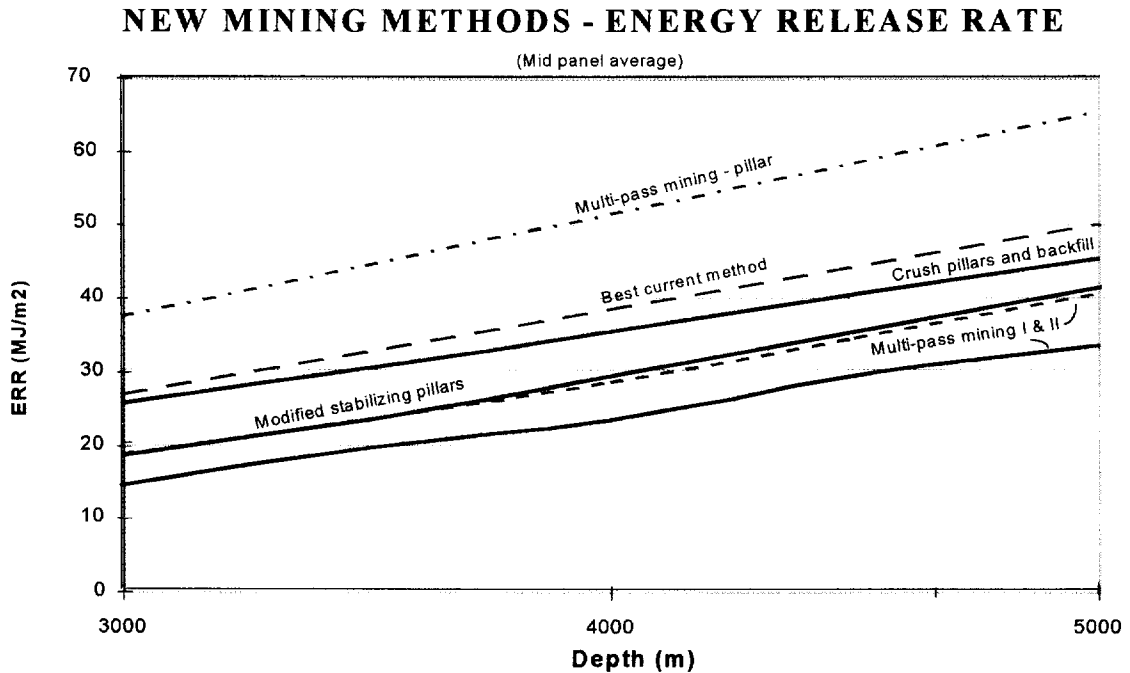
Figure 3.18   ERR comparison for proposed deep level mining methods.

ERR values for the multi-pass mining and modified stabilizing pillar methods are compared to the best current method in Figure 3.18 and show an improvement of between 30 and 40%. The phase three mining of the pillar in multi-pass mining is the major area of concern here. This could either be omitted or tackled with appropriately designed pre-conditioning. This would be carried out as part of phase 2 mining in which the pillar would be substantially de-stressed at the time of mining.

This curve also shows results for crush pillars and backfill with no stabilizing pillars (92% extraction), which shows an improvement over current methods, though not as good as the other methods described above. The amount of stope filling is reduced for these comparisons, thus results are a little conservative. Stope filling is 60% for crush pillars, 50% for multi pass mining and 30 % for modified stabilizing pillars.

NEW MINING METHODS - STOPE AREA CLOSURE
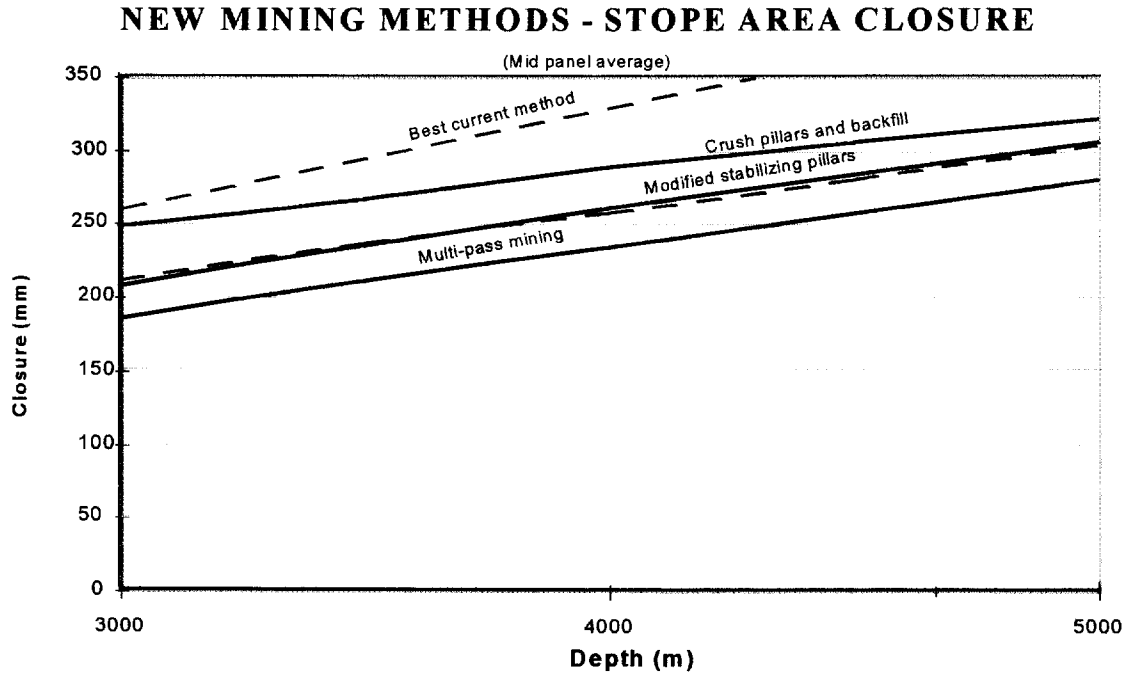
Figure 3.19 Stope area (20m) closure comparison for proposed deep level mining methods.

Stope area closure is shown in figure 3.19 where it can be seen that all the methods show a marked reduction in closure compared to current methods. This is advantageous as yielding face support such as rapid yield hydraulic props are more effective. Figure 3.20 shows a small reduction in face stress.

NEW MINING METHODS - FACE AREA STRESS
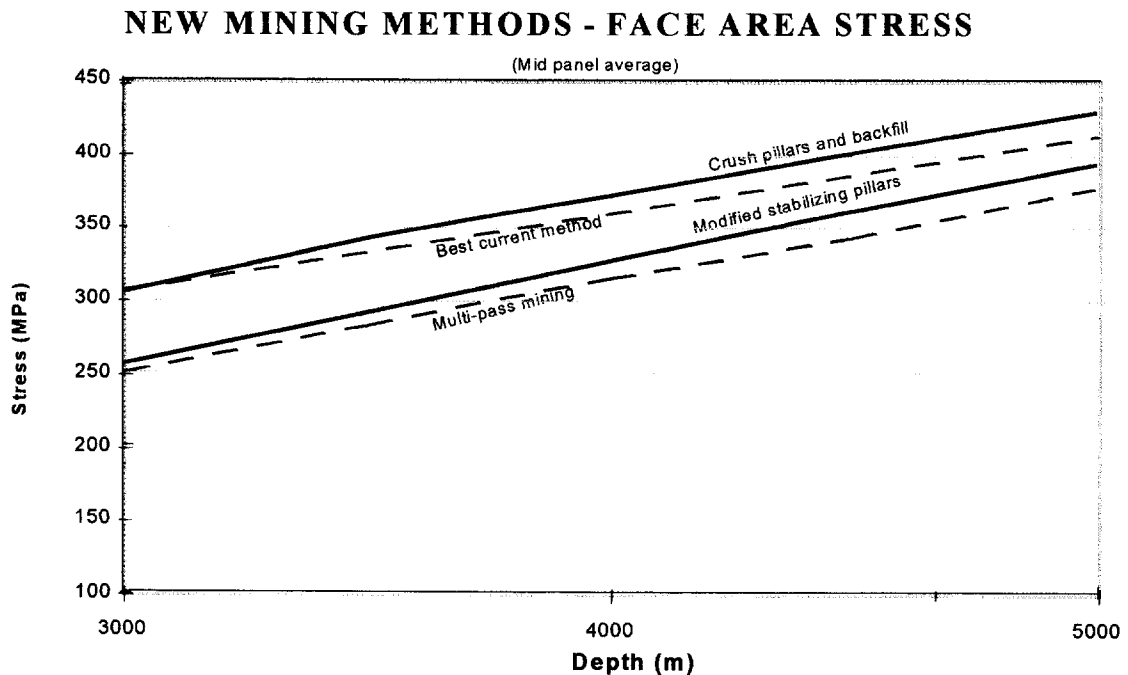
Figure 3.20 Face (5m) stress comparison for proposed deep level mining methods.

New Methods - Face area layout alternatives

To go with the above regional layouts are three alternative local or "in panel" layouts that warrant further consideration.
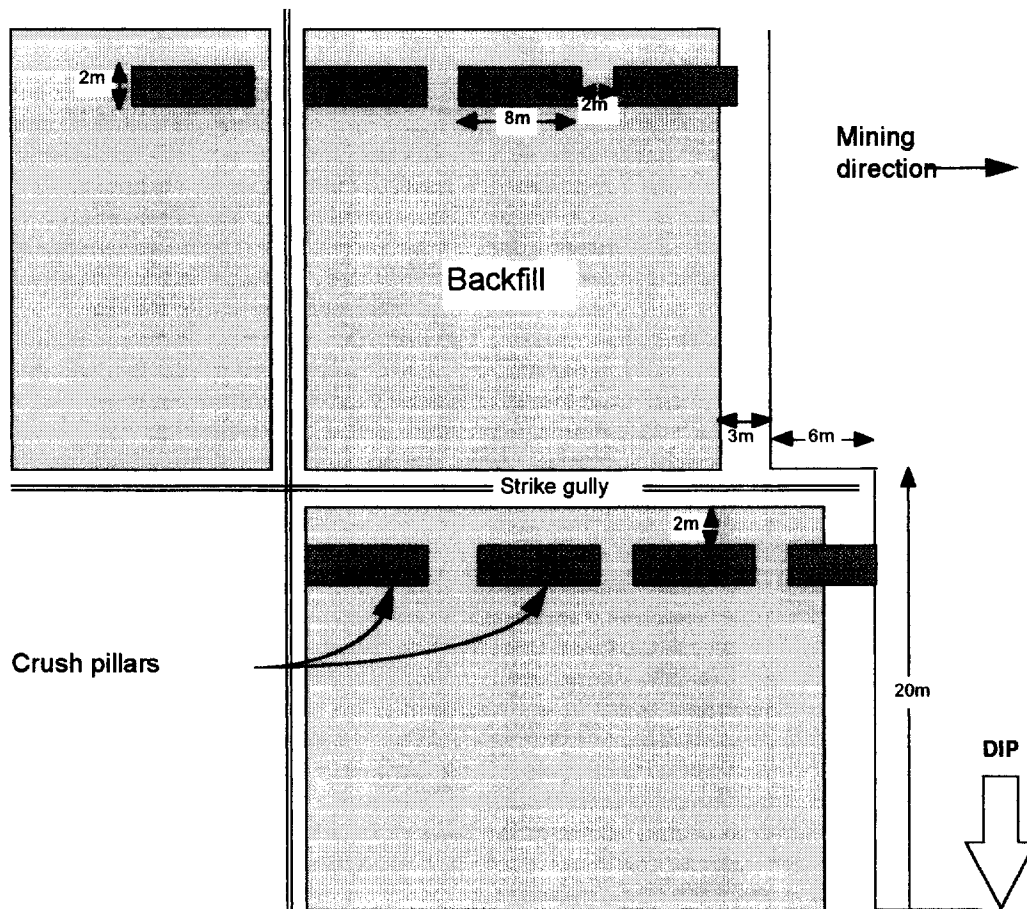
Figure 3.21   Crush pillars & backfill in panel layout

Figure 3.21 shows the crush pillar and backfill panel layout mentioned previously. In this 20 m panels are mined, with 2m by 8m crush pillars on strike, 2m on the downdip side of the strike gullies. These have been modelled with 60% stope filling using the same fill as before. The remainder of the face area requires local support according to current design methodology (Roberts, 1995).

This panel support may be used in either a "hard" or "soft" environment with either of the regional layouts presented.

The second "in panel" layout (Figure 3.22) makes use of short panels (no more than 20m), with extensive backfilling and with limited stope area access. Drilling, blasting and cleaning is all performed from the protection of well supported gullies. It is anticipated that this will be used in areas of very friable hangingwall.
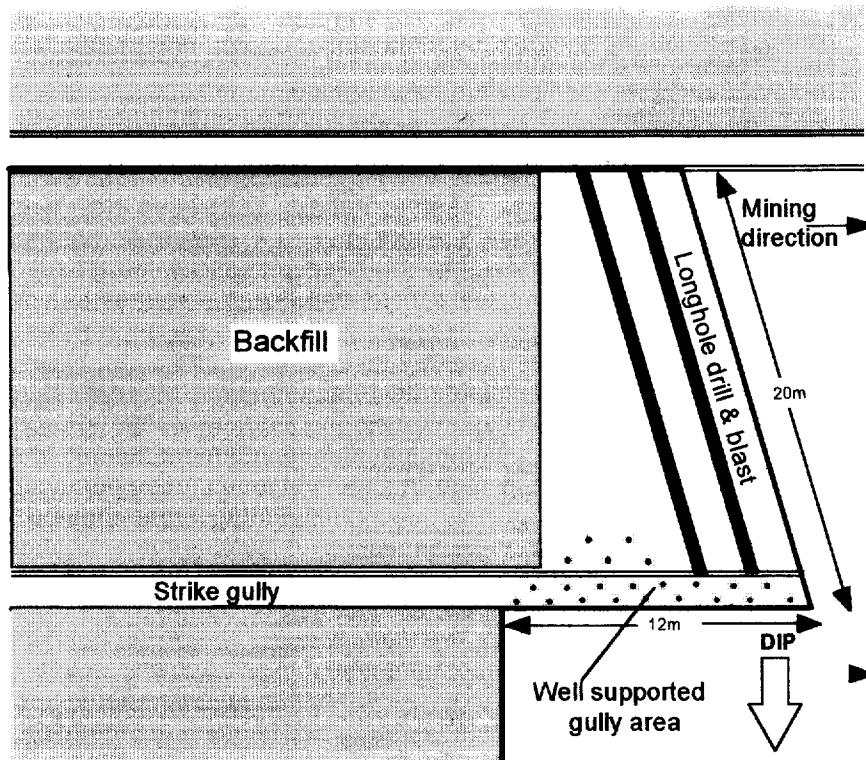
Figure 3.22 Longhole drilling & backfill in panel layout

The disadvantages of both methods above is that they are different from current practise, and will take time to learn. The third proposed layout has the advantage of being similar to current mining, with extensive stope backfilling supplemented by every 10 th blast remaining uncleaned on a staggered pattern. While this is unattractive from a production viewpoint, it is very easy to achieve. Alternatively, waste packing could be considered. This is illustrated in Figure 3.23.
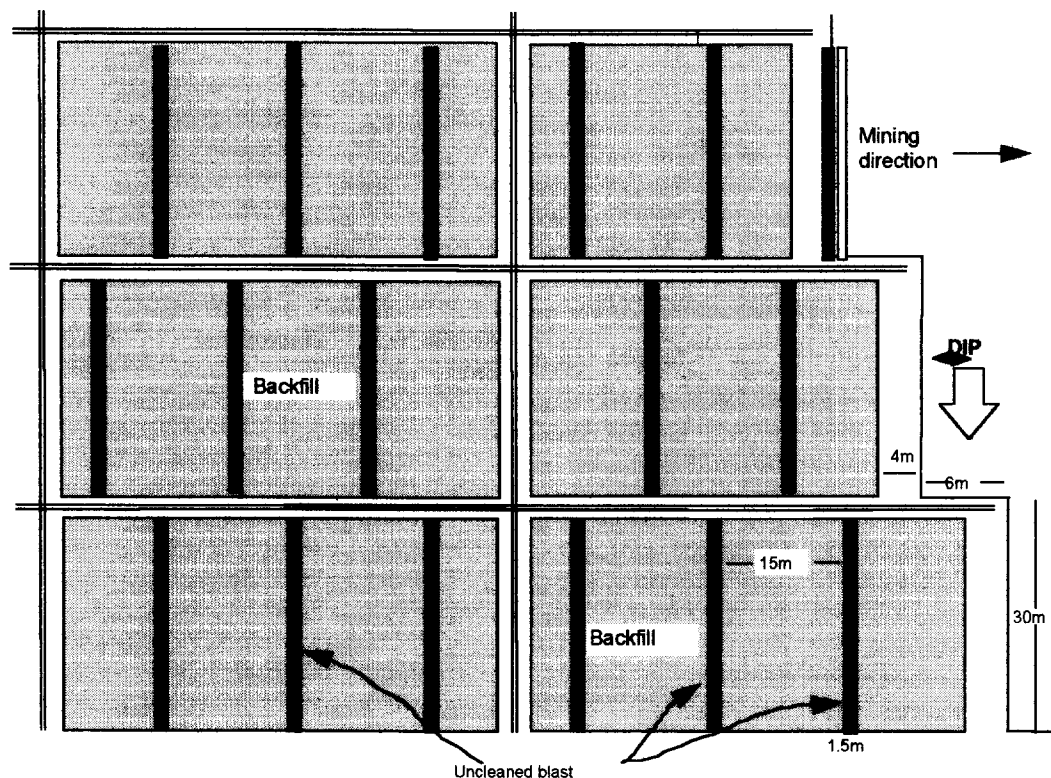
Figure 3.23 Left blast & backfill in panel layout.

While these regional and local layouts have yet to be proven in practise, they offer significant improvements in safety (ERR), they are practical and in some cases offer increased or total extraction.

3.5 Crush pillars & backfill

A program of laboratory and numerical modelling work has been carried out to investigate the behaviour of crush pillars confined by backfill with a view to incorporating these as part of a mining method at ultra-depth.

The crush pillar alternative is being considered because they are proven effective at shallower depths. At ultra-depth such pillars will be crushed ahead of cutting eliminating the risk of bursting. Recent findings confirming the effectiveness of backfill in reducing accidents (Gürtunca, 1995) coupled to the need to stiffen such fill for application at ultra-depth motivates the investigation of crush pillars in conjunction with extensive backfilling. This can give in excess of 90% extraction and promises to provide acceptable mining conditions. It is felt that the backfill will increase the strength of the crush pillars (borne out in this study) and that the crush pillars will in turn provide early stiffness to the face area improving local support.

Residual strengths were found to be consistently between 5 and 12 MPa corresponding to 2 - 6 % of the UCS as illustrated in Figure 3.24. These values are considerably lower than anticipated. These results vary little with changes in width to height between 1½:1 and 3:1. The larger width/height samples show a more marked tendency to increase in strength with increasing deformation.
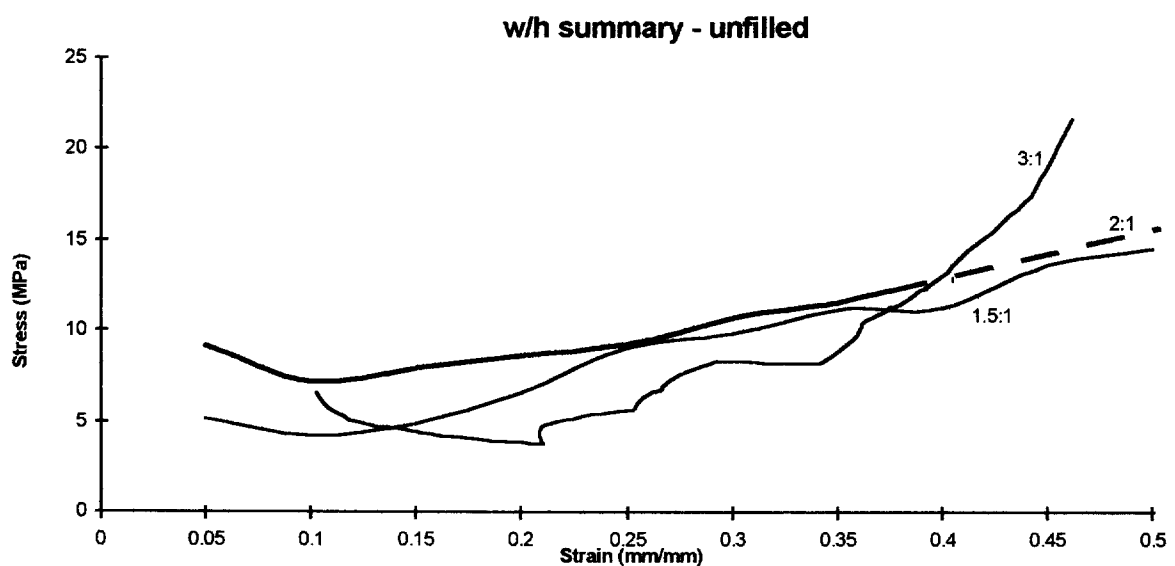

Figure 3.24   Laboratory results summary - residual strength of samples with no backfill for varied width to heights.

The strengthening effects of even very limited backfill are significant. The 1½:1 pillar being three times as strong with fill, with the 2:1 and 3:1 cases some 40 and 75 times stronger than without backfill respectively (see Figure 3.25).
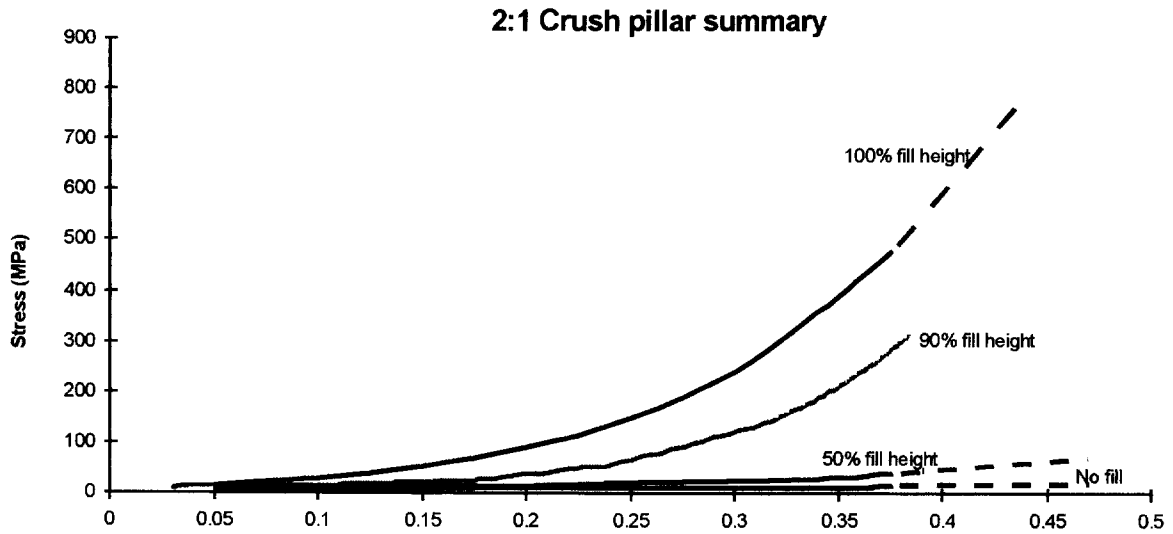

Figure 3.25   Laboratory results summary - 2:1 width to height with backfill confinement of variable height.

The effects of varying the fill height are shown in Figure 3.26. In cases where the fill is 90% of the sample height, the above figures are reduced by about 40%. Filling to only half the sample height provided a three fold strength increase.
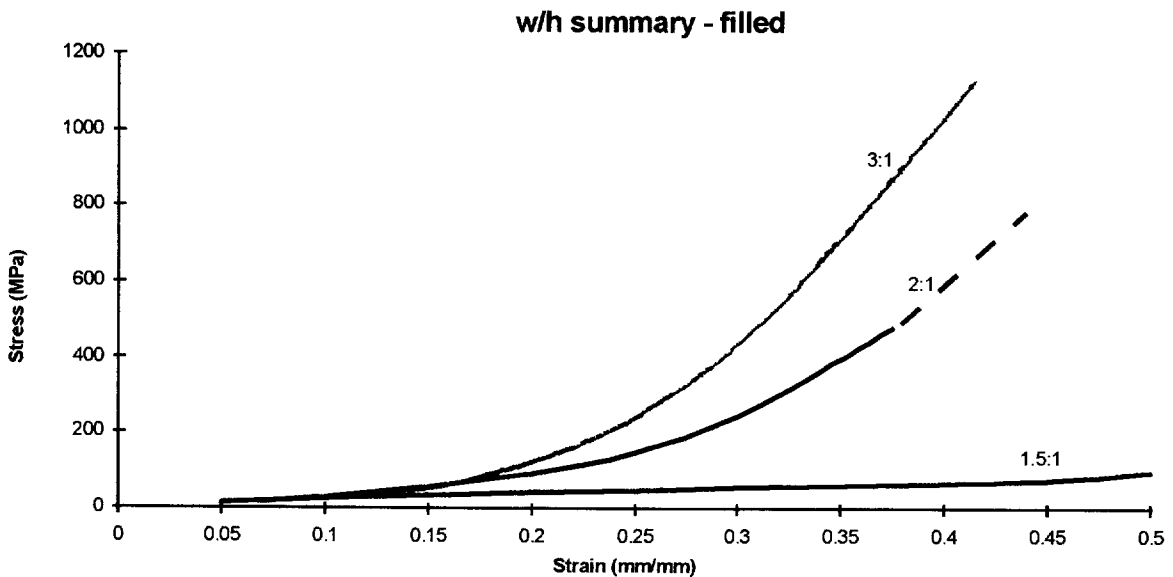
Figure 3.26   Laboratory results summary - width to height varied with backfill confinement.

It is felt that these results encourage the application of crush pillars to some specific mining conditions both at high stress and in deep levels. A paper on this work awaiting publication is given in Appendix 7.

3.6 AAC contract - possible stoping method and support for ultra-deep tabular reefs.

(Work carried out by A. J. Spearing towards PhD, 1993)

It is known from geological drilling on the Witwatersrand Basin that relatively high grade gold orebodies exist at ultra-depth (over 4 000m below surface). Whether these deposits can ever be economically and safely exploited is much in debate at present, due mainly to:-

- the unacceptable rock related accident rate at current mining depths, (safety),
- rock mechanics consideration in general,
- ventilation considerations,
- a basically constant gold price in a relatively high inflation rate, (economy).

Stope support on macro (regional support) and micro scales (face, gully and internal support) is the most vital consideration for successful mining at ultra-depth, in addition to an effective rockburst management system.

Current methods reviewed

The current stope support systems were initially studied in this report to investigate the success of such systems and their general applicability at ultra-depth.

<u>Regional support.</u>

- The common regional support on deep mines, involving the leaving of in situ strike stabilising pillars, has not been very successful and would not be appropriate at ultra-depth due also to financial constraints (leaving 30% in pillars could reduce pre tax profit by 20%). This is due mainly to seismicity associated with pillar foundation failure, and the relatively low overall extraction rate that would be achieved.
- Timber packs as internal support are generally adequate at current mining depths but would not be adequate or cost effective at ultra-depth. Backfill would provide a better support systems that could also act as a regional support, and effectively reduce the heat ingress and ventilation costs.

<u>Face and gully area.</u>

- Face support is generally too far from the stope face at present and is sometimes inadequate as can be seen by the unsatisfactory safety record of the gold mining industry. This implies that the current systems in use will be totally inadequate at ultra-depth due to the probable increase in general seismicity. The use of diagonal blast barricades and water jet assisted scraping would be necessary at ultra-depth to ensure that the rapid yield hydraulic props (with headboards) could be installed and maintained close to the advancing stope face. The general areal coverage currently at the face is also a cause of concern and would be totally inadequate at ultra-depth, and hence the need for correctly designed long axis headboards on props in the stope face area.

- The support of the gully hangingwall at present needs to be improved since current standards employed will be totally inadequate at ultra-depth. The gully shoulder support consisting usually of long axis packs is generally acceptable at present mining depths but may not be the most cost effective solution at ultra-depth. A relatively high early strength backfill appears a better support systems for gullies.

A possible mining method and support strategy at ultra-depth

The use of backfill was identified as a major component in any ultra-depth mine. Silicated backfill was found to be the most performance and cost effective fill type, supplemented by concrete fill ribs (at relatively high stoping widths only). The silicated backfill system has been already introduced on some deep mines and the results to date have been encouraging.

The extensive use of bracket pillars on adverse geological features was also identified as a necessary from of regional support in addition to the backfill. The need for bracket pillars would be identified mainly by past experience with the same feature (if applicable) and /or relevant seismic data. The design of such pillars requires more research and depends on the nature and properties of the feature and the surrounding rock mass.

The optimum gully shoulder support was found to be silicated backfill supplemented by an active elongate type of support. This has also been tested on a deep mine and found to be cost effective and safe at relatively high stoping widths.

In high stoping width areas at ultra-depth, a double cut mining method must be adopted. This is where a narrow cut is taken on the top reef contact and the remainder of the reef extracted in a destressed environment behind the face using trenching. This makes the face support more effective.

Finally, cost comparisons were undertaken to compare the support cost of the method proposed and those commonly in use on deep mines at present and results were found to be similar. Hence there was no reason for support costs at ultra-depth to be significantly higher than those on deep mines. This could be achieved by moving the emphasis away from expensive and labour intensive pack based systems, to backfill with relatively intensive face and gully support. With the use of diagonal barricades and water jet assisted cleaning, productivity and safety could be realistically improved even at ultra-depth.

It is therefore concluded that the rock mechanics problems of mining at ultra-depth can be successfully and cost effectively resolved.

A summary of this work is given in Appendix 4.

4. REMNANT STABILITY ANALYSIS

Work on the assessment of remnant stability was initially motivated by the high percentage production across the industry from remnants, isolated blocks and difficult to mine areas. Figures range from 20 to over 40% of production in different areas, with these figures increasing in some areas.

Remnants may be highly stressed even at moderate depths and are often hazardous to mine. In OFS and Klerksdorp in particular, many remnants are located adjacent to faults and dykes or at the intersections of faults and dykes. Remnants are most often not planned as such, but are left because of mining difficulty or hazard. In some cases remnants become easier to mine with time, while others remain dangerous. As mines get "older", more of their available ore-reserves are in remnants which make up an increasing percentage of their production.

4.1 Background

Legge and Spottiswoode (1987) report an increase in the Gutenberg-Richter b-value in the formation stages of a remnant based on monitoring of a Klerksdorp remnant. Despite the fact that this work was carried out using a dedicated micro-seismic system, using seismic events with M<0, it was hoped that the change in frequency magnitude distribution this represented would be observed in data available from regional mine seismic monitoring, for which most events have M>0. Subsequent analysis of a problematic remnant in the OFS was carried out by Minney and Naismith (1993) who assessed a number of seismic parameters as indicators of the remnant stability. They found b-value and cumulative seismic data to be the most reliable indications of stress change in a remnant.

4.2 Approach

A number of remnants have been back analysed - initially to assess the use of the b-value as a measure of remnant stability as previous work had indicated the potential use of the b-value as an indicator of remnant stability. No significant correlation has been found - presumably due to the limited sensitivity of mine seismic networks in capturing small events. The study was then extended to include a large number of parameters - both from seismic records and from MINSIM-D modelling. Raw data, moving averages, time and number of event intervals have been used. A spreadsheet has been compiled to facilitate the computation and plotting of these trends. Correlation has been observed in some cases between seismic event distribution and parameters such as P/S moment & energy ratios, seismic viscosity and remnant stress. Results to date are inconclusive as such correlations do not always work. Many more remnants need to be included in the study to add confidence to these trends. Figures below show example outputs from some of 15 remnants back

analysed. Individual cases show promising correlation between seismicity and parameters such as b-value, seismic viscosity & P/S ratios. There are, however counter examples for each case.

It was hoped that such values would firstly indicate the stage at which large events on a remnant can still be expected, and secondly the stage at which the remnant itself is "safe", but seismicity on nearby structures might increase. Progress in this area remains disappointing. Few trends of significance have been noted.

4.3 Results

Selected results are given below, principally those with the most promising correlations or trends.

Figure 4.1 shows the location of a Klerksdorp remnant wedged between several small dykes and faults. This was mined up-dip over several years with much seismicity as shown on Figure 4.2.

KLERKSDORP REMNANT 2
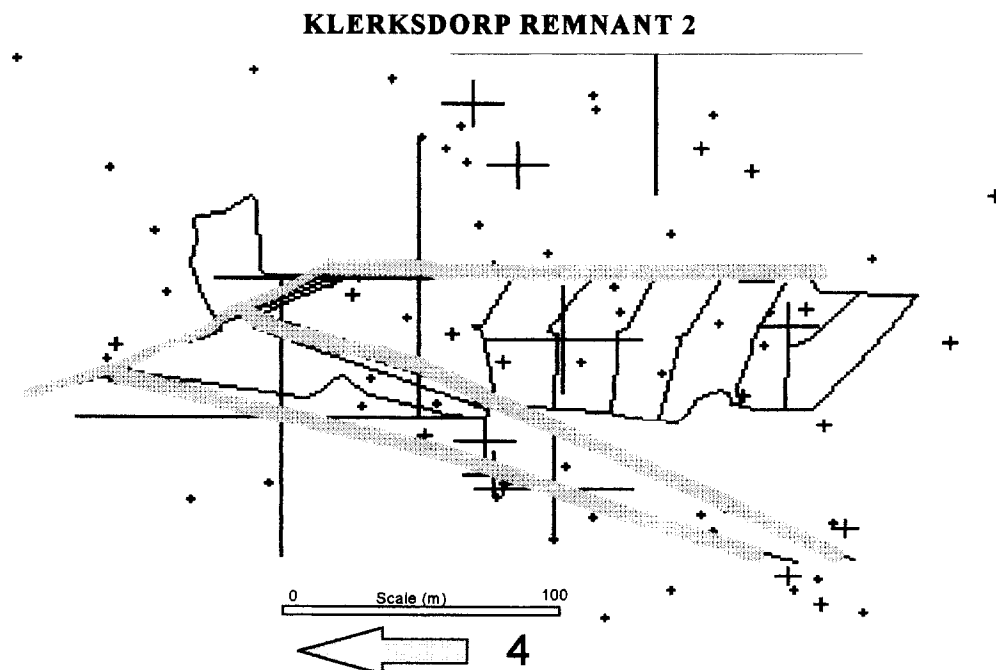
Figure 4.1   Klerksdorp remnant 2 located at the intersection of several faults and dykes. Mining faces and event locations are shown.
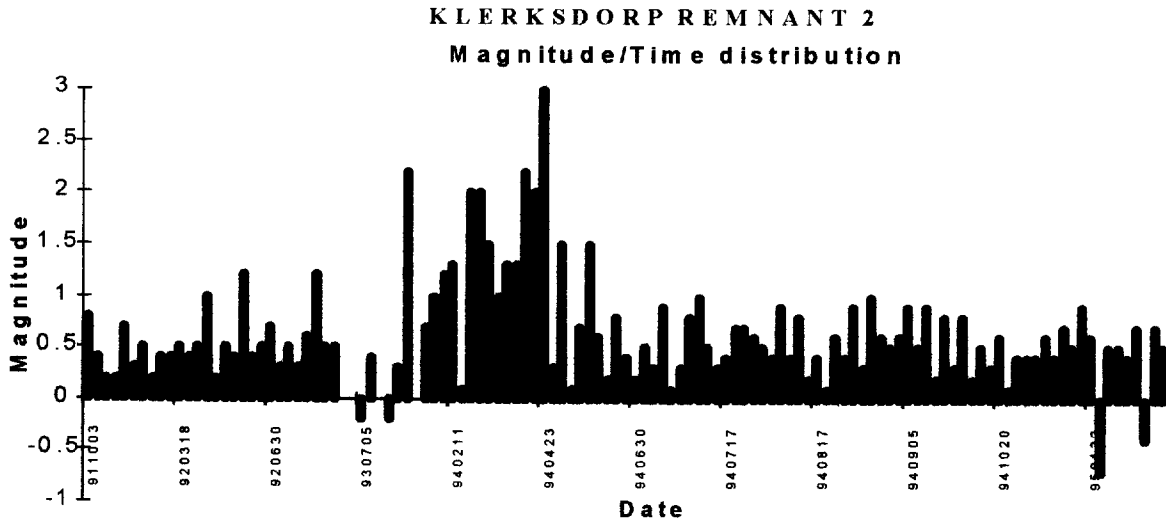
Figure 4.2 Event time distribution for Klerksdorp remnant 2.

A trend of increasing and then decreasing b-value is observed in the 10 point moving average, though less significant in the 15 & 20 point lines - see Figure 4.3 This b-value decrease perhaps suggests that events are moving off the remnant face (b=1) to nearby geological features (b=0.5). Figure 4.4 shows a similar trend in seismic viscosity and one can argue that these offer a good correlation with the observed increase and subsequent decrease in seismicity. Figure 4.5 shows a gradual increase in the ratio of S to P moment which supports the conclusion from Figure 4.3.
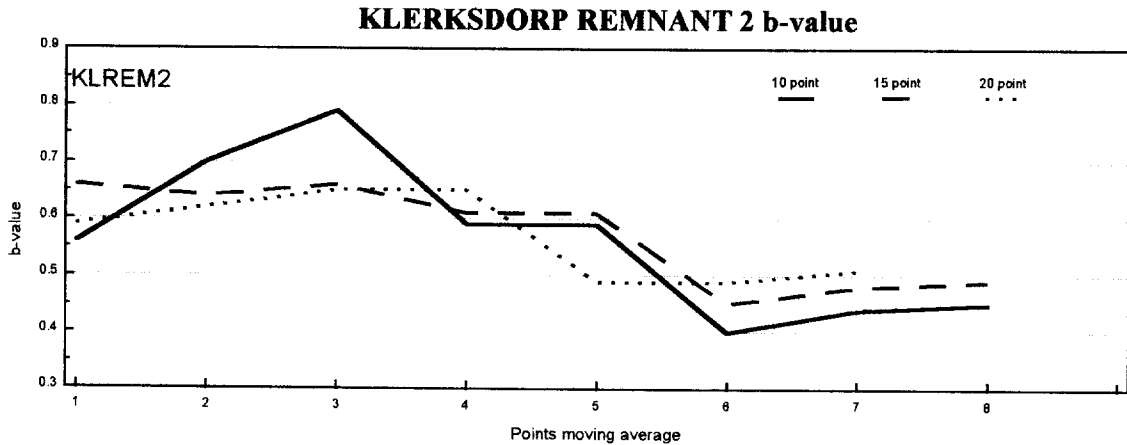
Figure 4.3 b-value moving average trends for Klerksdorp remnant 2.
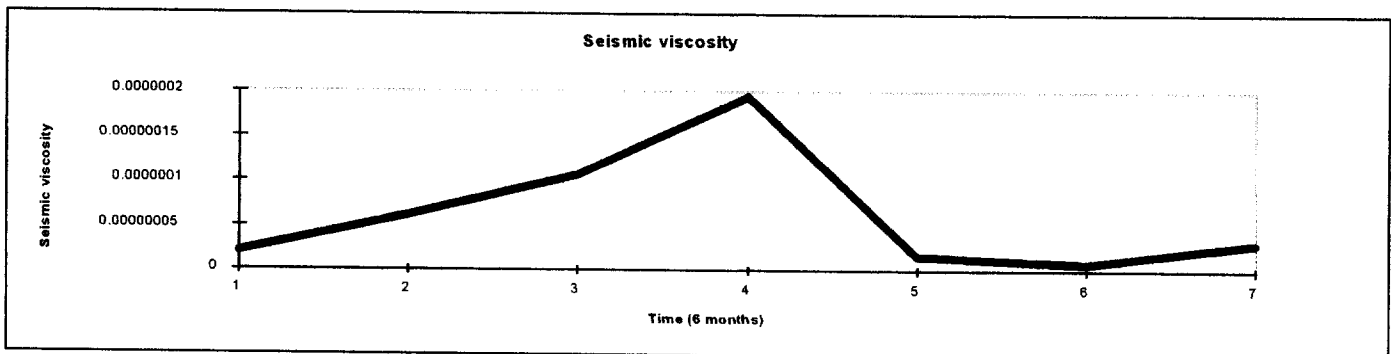
Figure 4.4 Seismic viscosity for Klerksdorp remnant 2.

KLERKSDORP REMNANT 2
Moment ratio S/P
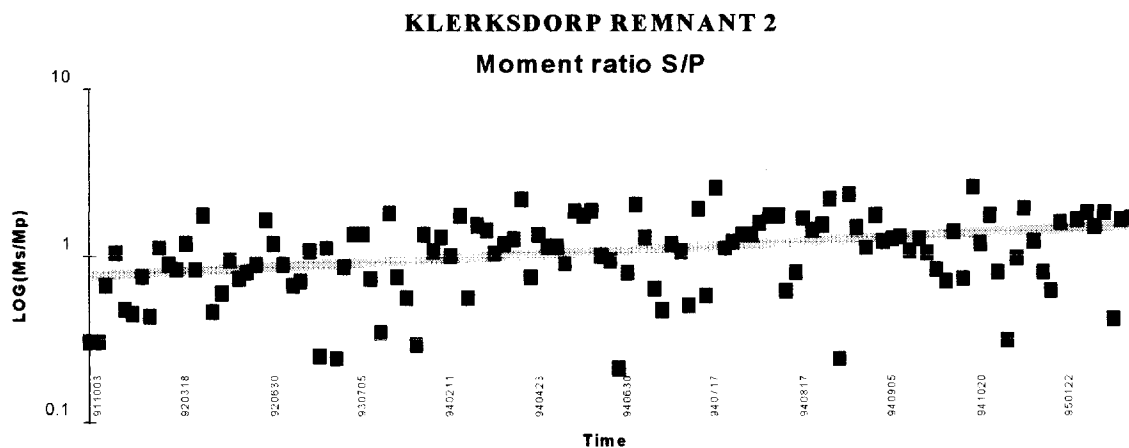
Figure 4.5 S/P moment ratio for Klerksdorp remnant 2.

A second Klerksdorp remnant studied is illustrated in Figure 4.6 and shows the mining both up dip and on strike of a long thin remnant adjacent to a 30m dyke-fault. Major seismicity appears to be related to the structures, with the largest event plotting on the intersection of this dyke and a fault to the east of the remnant. Figure 4.7 shows the time distribution of seismicity to have large events throughout the monitored period.

KLERKSDORP REMNANT 3

Depth ~ 2100m
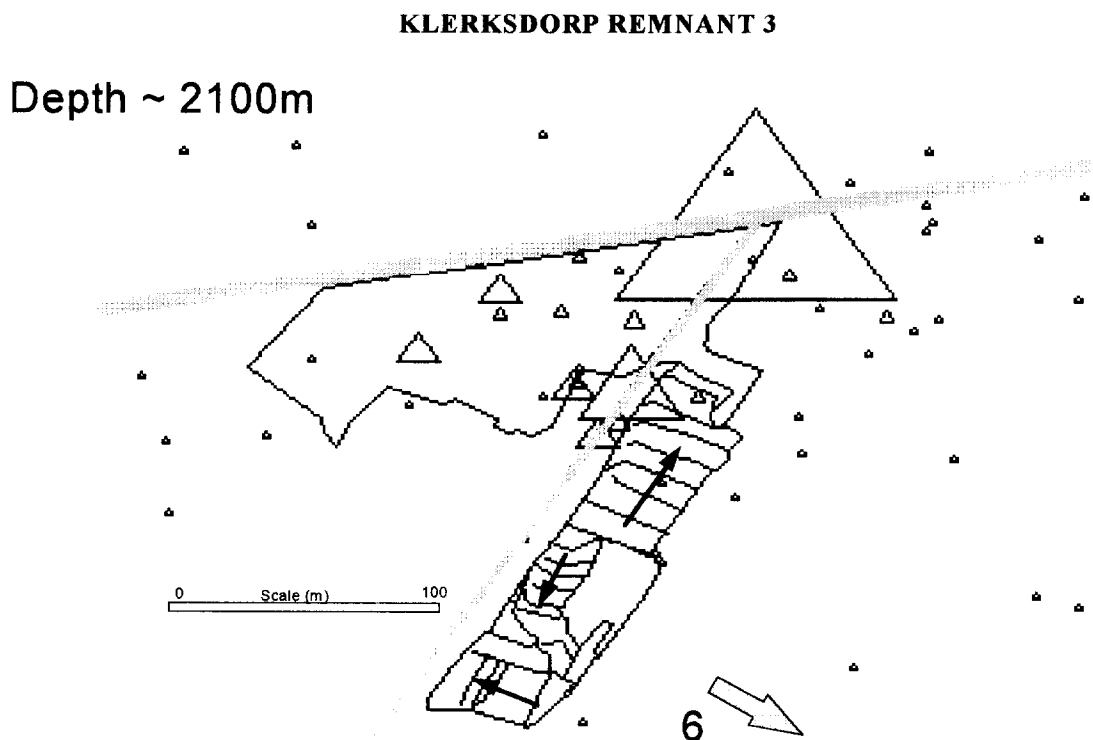
Figure 4.6 Klerksdorp remnant 3 located adjacent to a fault. Mining faces and event locations are shown.
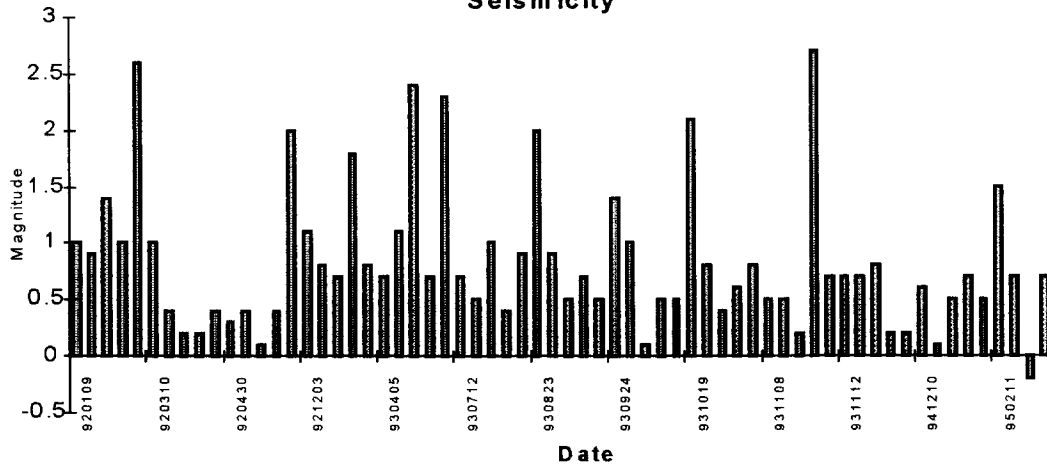
KLERKSDORP REMNANT 3
Seismicity

Figure 4.7 Event time distribution for Klerksdorp remnant 3.

Moving average b-value and seismic viscosity plots are shown in Figures 4.8 and 4.9 respectively. Both show trends that, unlike the previous study, do not correlate well with the observed seismic distribution.
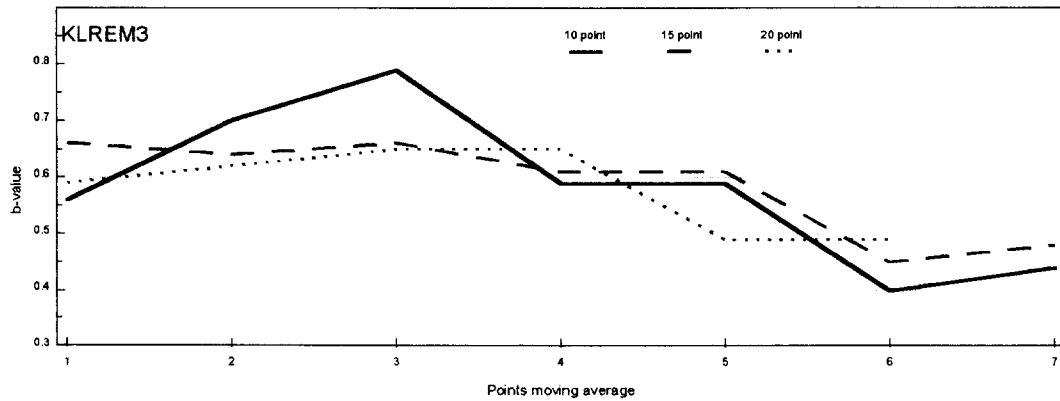
KLERKSDORP REMNANT 3 b-value

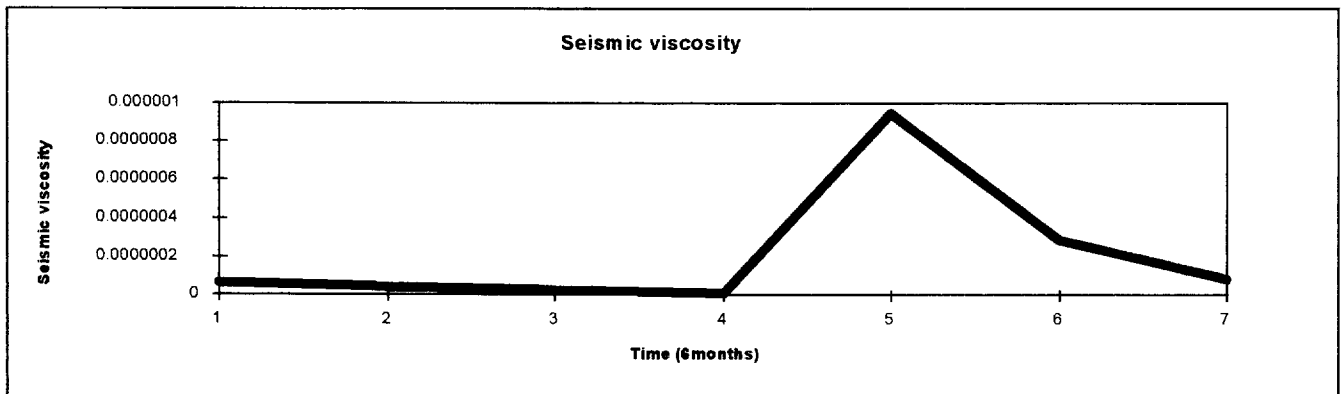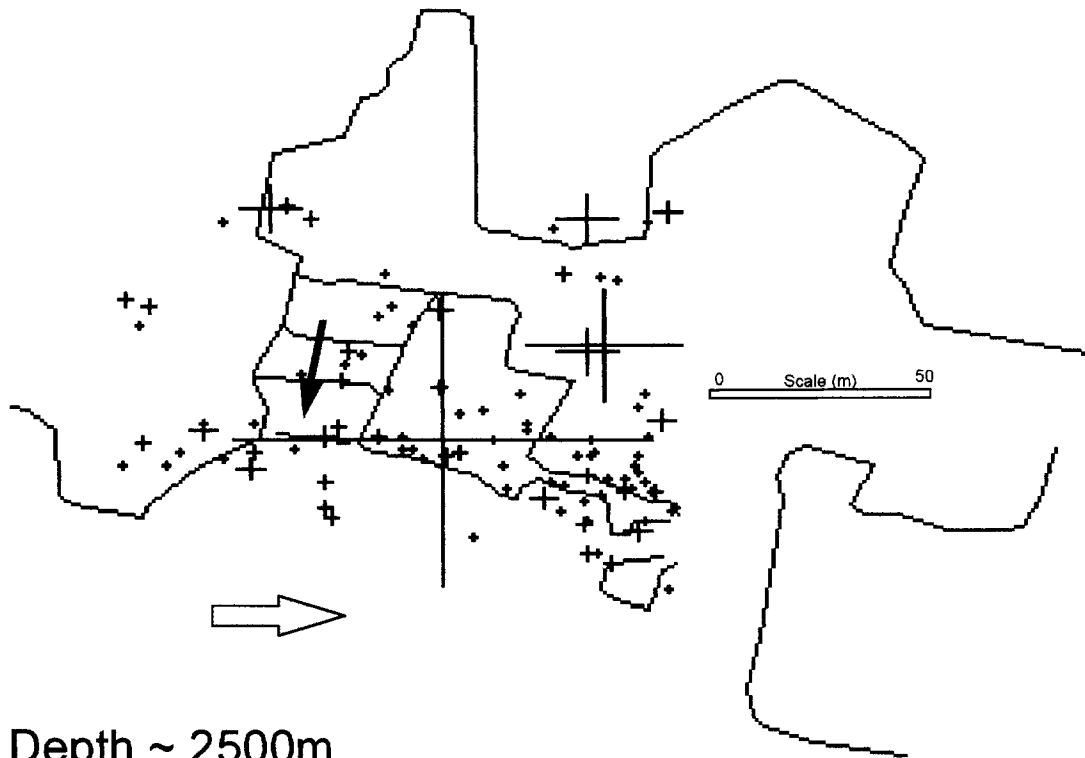Figure 4.8 b-value moving average trends for Klerksdorp remnant 3.

Seismic viscosity

Figure 4.9 Seismic viscosity change with time on Klerksdorp remnant 3.

OFS REMNANT 1

Depth ~ 2500m

Figure 4.10 OFS remnant 1 located adjacent to a fault. Mining faces and event locations are shown.

The next example is a OFS remnant adjacent to a fault illustrated in Figure 4.10 above. Mining on brest angled at 90° to the fault approaches holing to make this into an island remnant from a peninsula remnant. The event distribution given in Figure 4.11 shows a dramatic decrease in seismicity after February 1994. The b-value shows a slight decrease followed by a significant increase perhaps indicative of the change in remnant stability. Study of other parameters associated with this remnant showed no trends of note.

OFS REMNANT 1
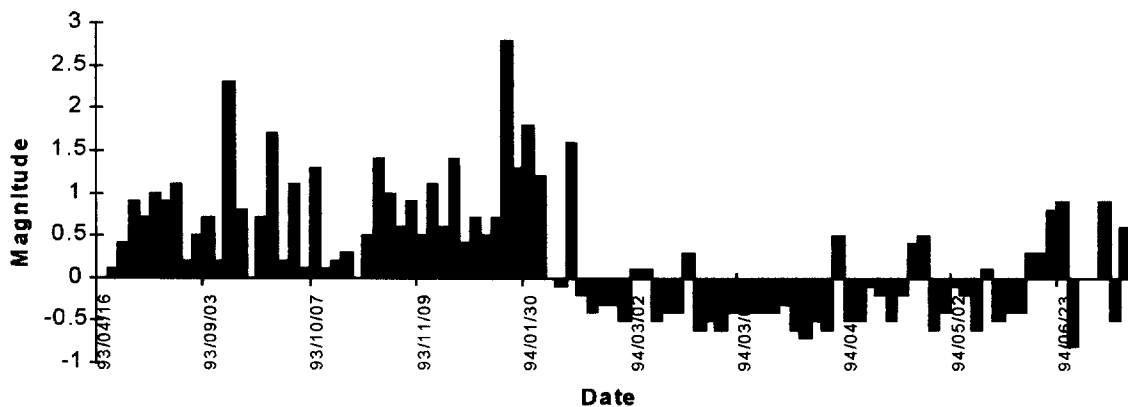**OFSREM1 - Event distribution**

Figure 4.11 Event time distribution for OFS remnant 1.
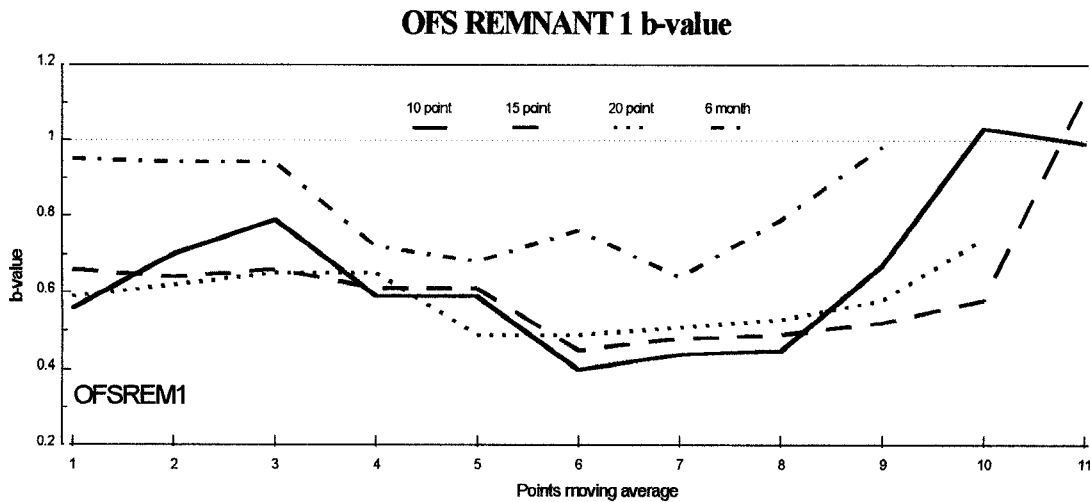
OFS REMNANT 1 b-value

Figure 4.12 b-value moving average trends for OFS remnant 1.

Another OFS remnant, having a similar layout to the example above, is illustrated in Figure 4.13. Seismicity appears strongly related to the holing of the remnant as can be seen in Figure 4.13.
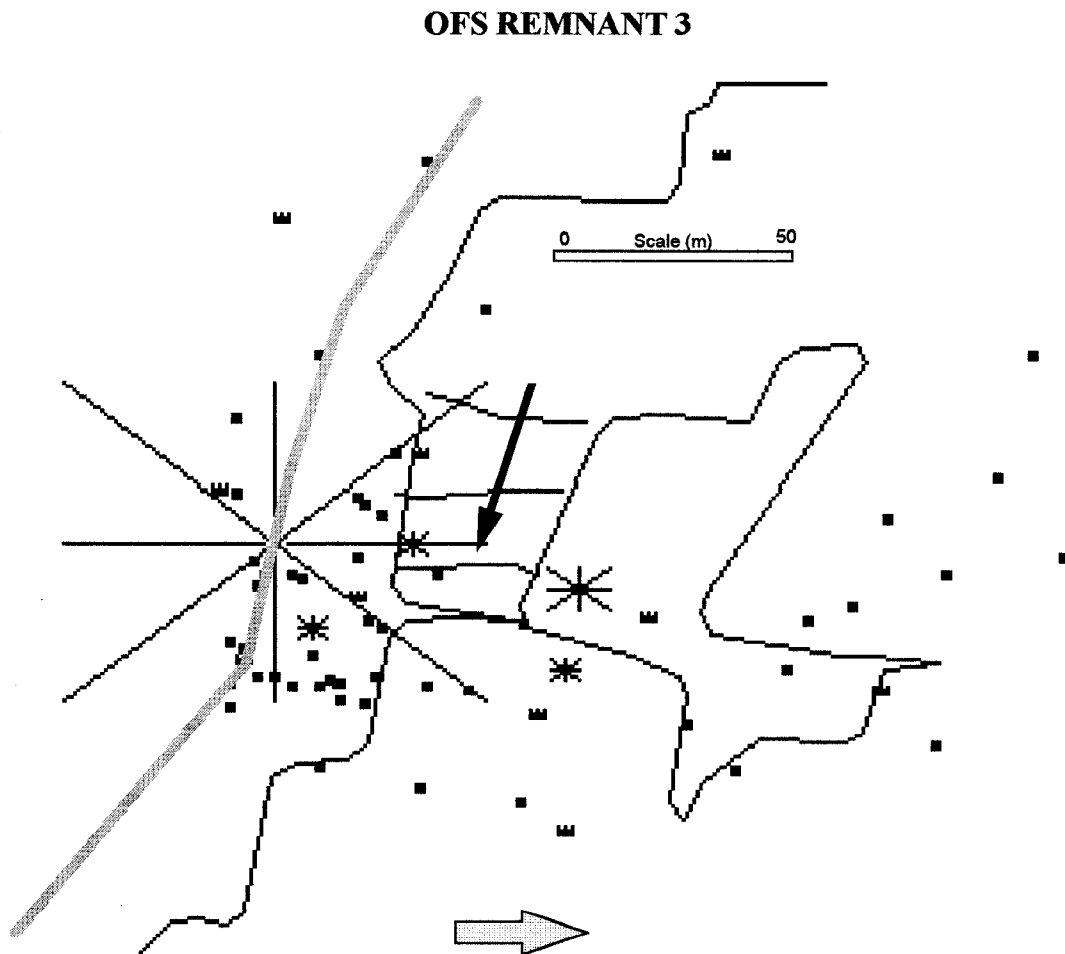
OFS REMNANT 3

Figure 4.13 OFS remnant 3 located adjacent to a fault. Mining faces and event locations are shown.
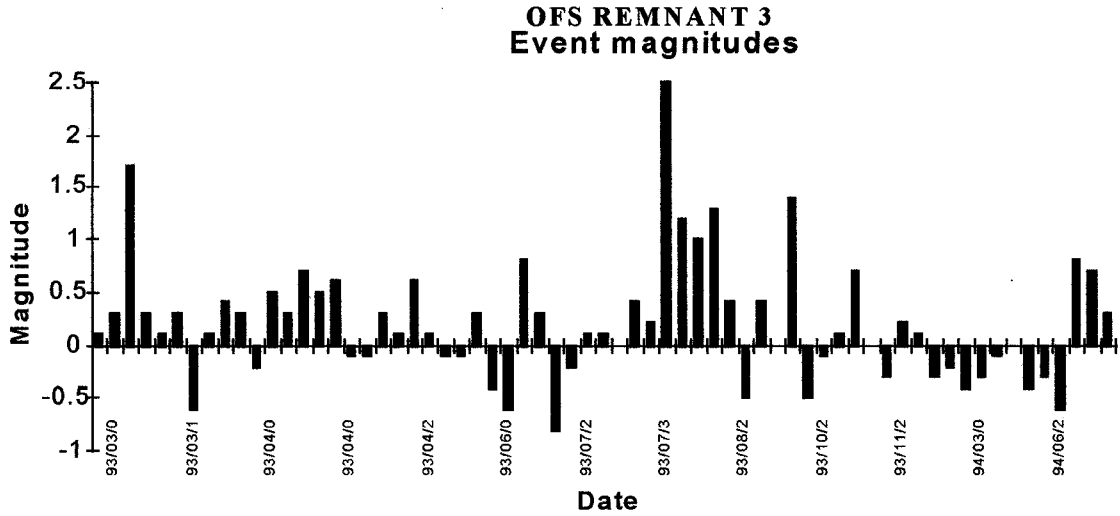
OFS REMNANT 3
Event magnitudes

Figure 4.14   Event time distribution for OFS remnant 3.

The b-value drops initially then increases slightly as shown in Figure 4.15 - though this is not marked. A much more significant correlation is indicated in seismic viscosity below in Figure 4.16.
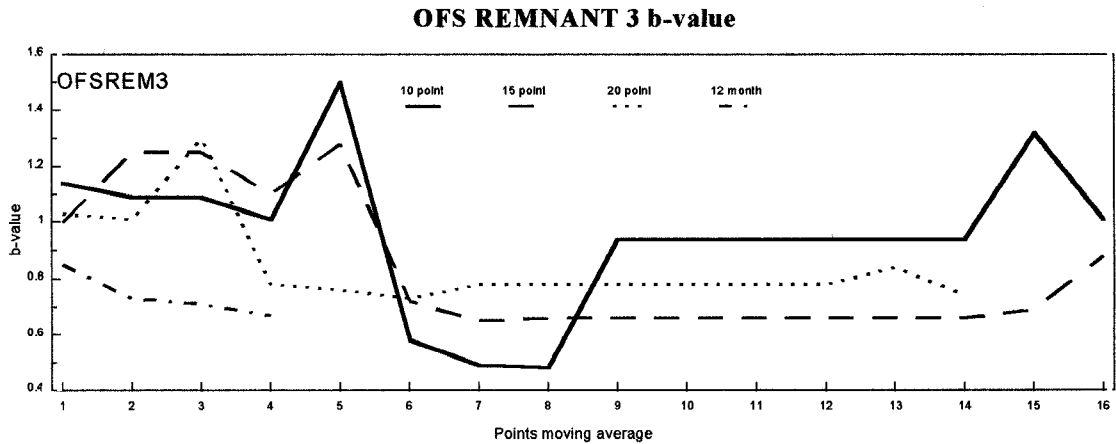
OFS REMNANT 3 b-value

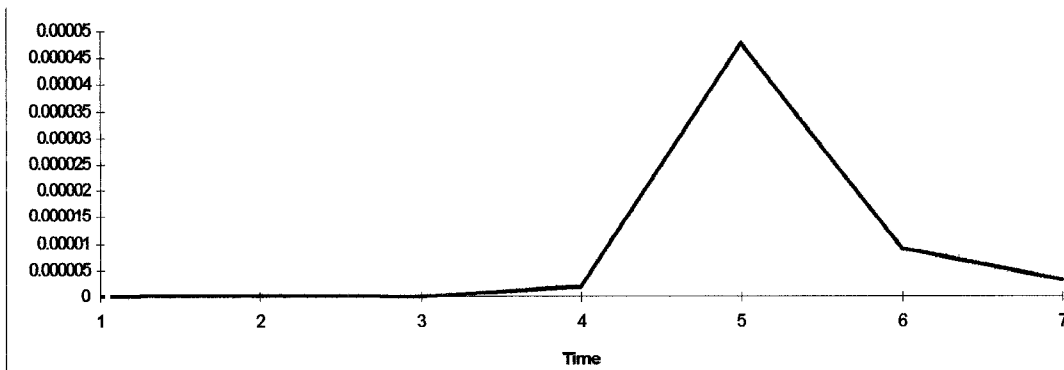Figure 4.15   b-value moving average trends for OFS remnant 3.

Figure 4.16   Seismic viscosity trends for OFS remnant 3.

An increasing trend in the S/P ratios indicating a shift in seismicity from remnant faces to adjacent geology is evident in Figure 4.17.
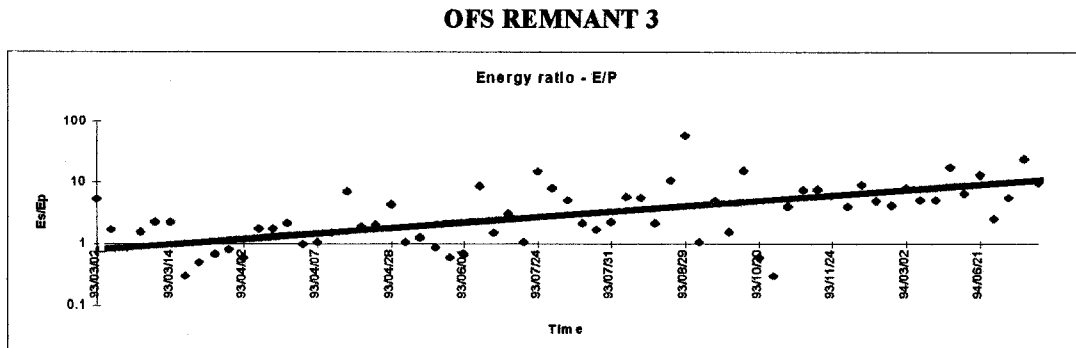
OFS REMNANT 3

Figure 4.17   P/S energy ratio trends for OFS remnant 3.

The above trends in siesmic analysis illustrate the better examples of correlation between remnant event distribution and seismic parameters. While good correlation is obtained from b-value, seismic viscosity and S/P ratios in some cases, there remain a number of counter examples and trends. The major problems with this analysis is lack of resolution of mine wide seismic systems in capturing small events and small datasets associated with most remnants. Monitoring remnant behaviour over a longer time may improve the above.

4.4 General

With the disappointing results obtained above, some other approaches have been tried, with good results in some cases, and these are outlined below.

The first example below from the Carletonville area (Figure 4.18) shows the mining of a peninsula remnant.
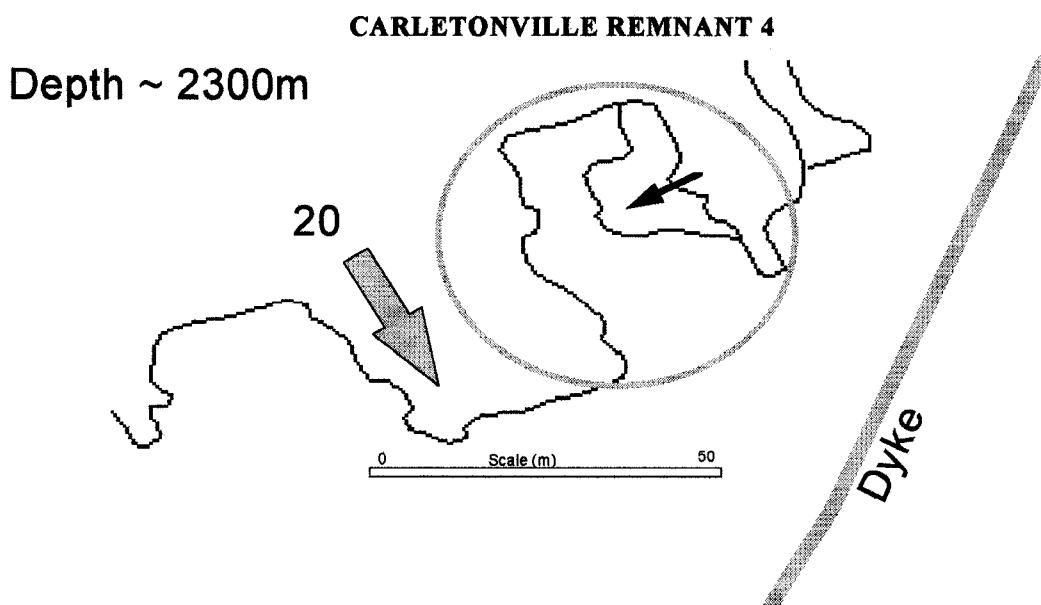
CARLETONVILLE REMNANT 4

Figure 4.18   Carletonville remnant 4 - a peninsula remnant showing direction of mining.

One can see mining narrowing the centre of the peninsula remnant, which in this case increased remnant stress to the point of failure in month 5 (see Figure 4.19). A more detailed assessment of the case is documented in a CSIR rockburst task force report.
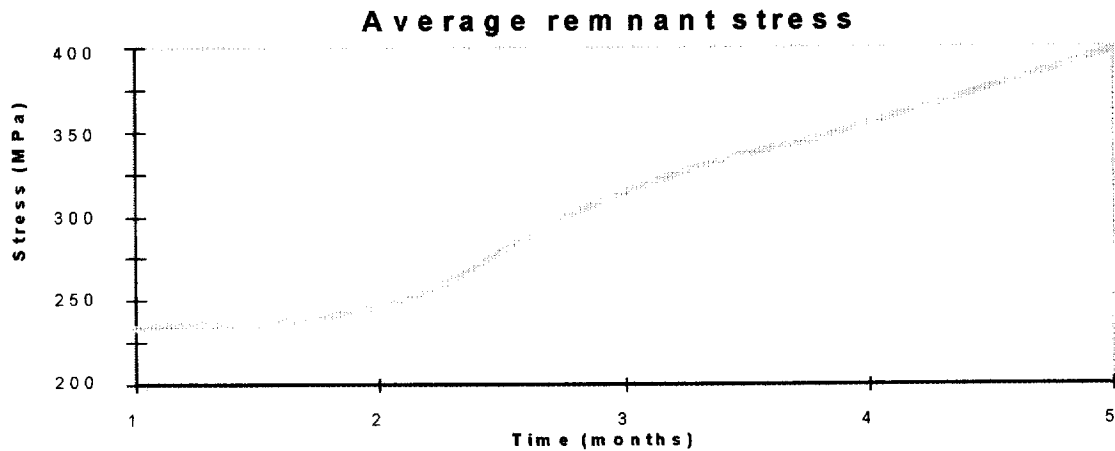
Average remnant stress

Figure 4.19   Increase in remnant stress with mining prior to remnant failure.

Depth ~ 2300m

Fault
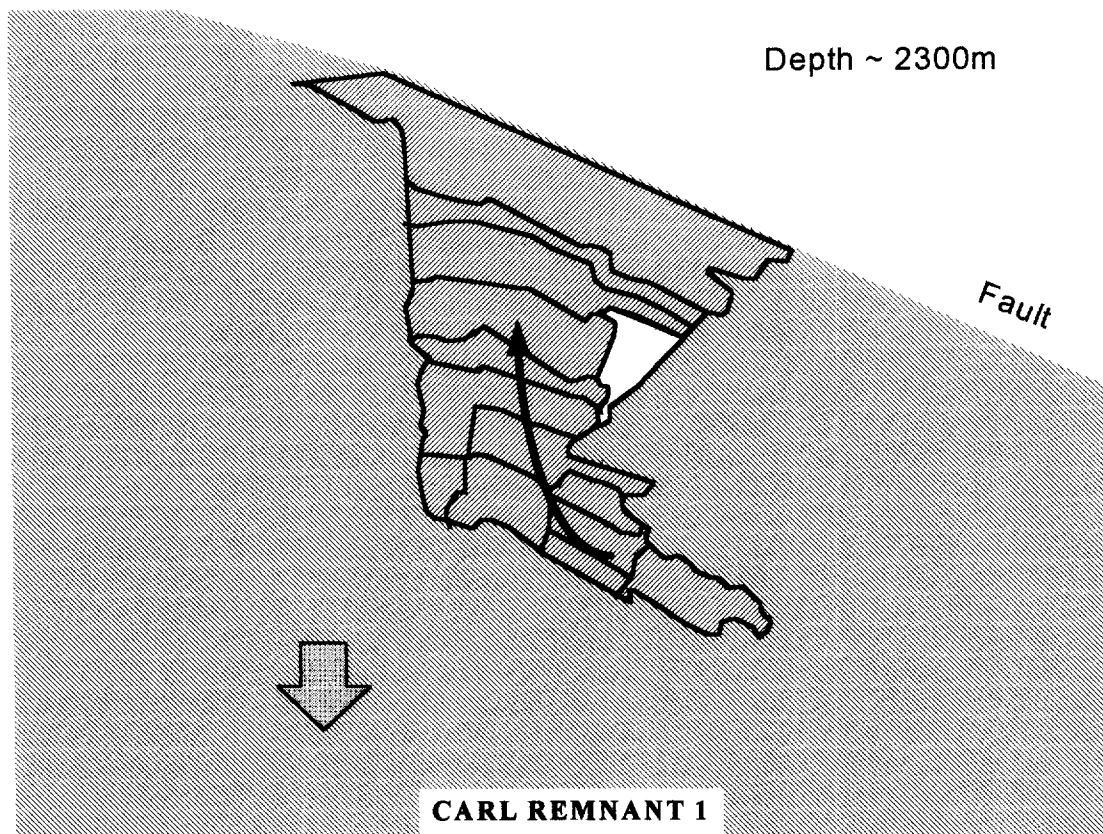
CARL REMNANT 1

Figure 4.19   Carletonville remnant 1 - a peninsula remnant showing direction of mining.

Figure 4.19 shows the layout of a second Carletonville remnant adjacent to a fault. Mining in the vicinity took place over many years around the remnant until final extraction. Figure 4.20 shows a good correlation between mining influence and seismicity on the fault. Areas of poor correlation correspond to mining away from the feature. Changing the weighting to account for mining direction improves the correlation, shown in Figure 4.21. An approximately linear relationship between

mining influence and log of fault seismic energy can be seen in Figure 4.22. A similar analysis was carried out on a remnant in Klerksdorp, yielding a poor correlation.

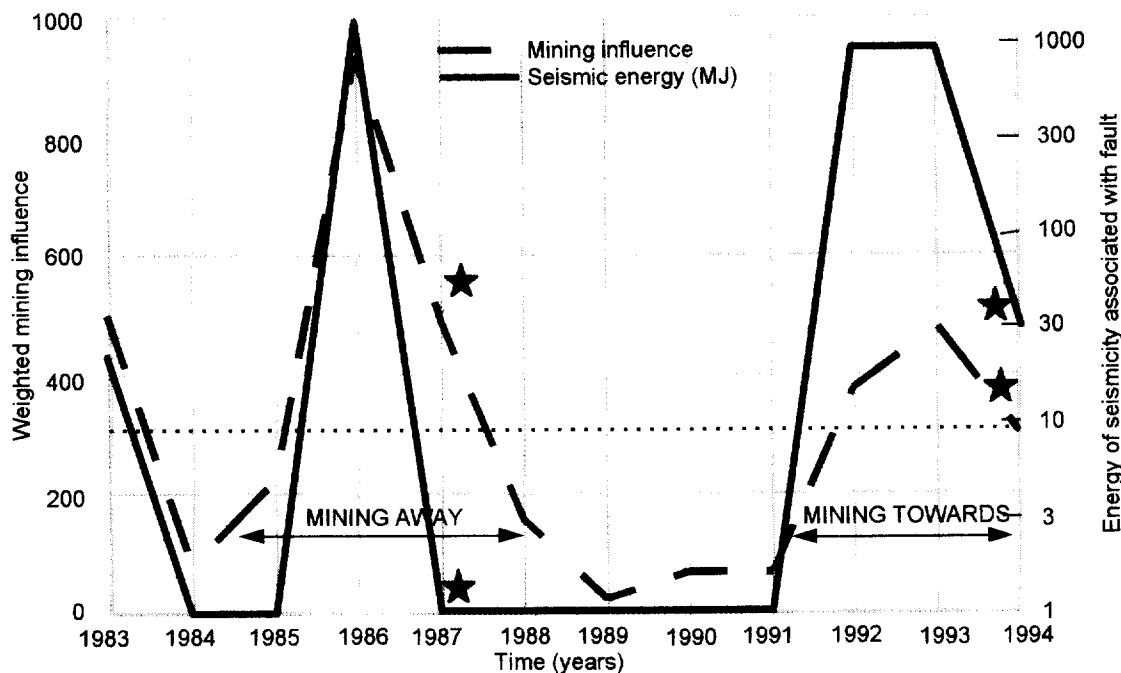Figure 4.20 Plot showing correlation between mining influence and seismicity on adjacent fault.
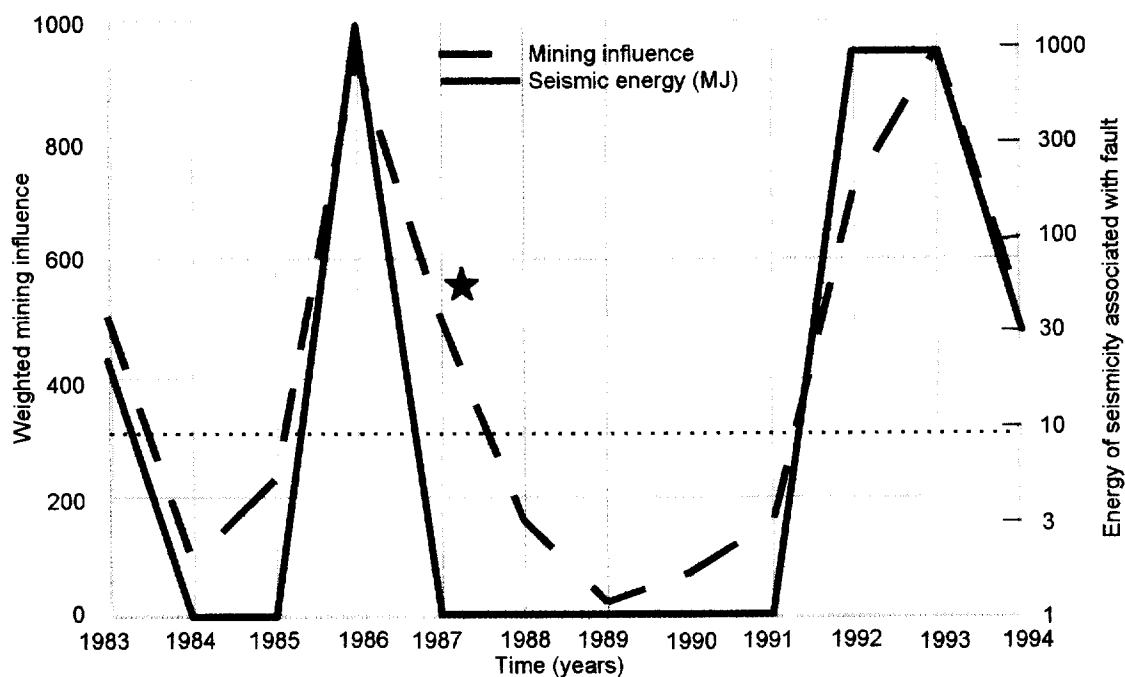

Figure 4.21 Correlation between mining influence improved to account for mining direction and seismicity on adjacent fault.

10000

1000

100

10

1

0.1

Log (Seismic energy) MJ

0   100   200   300   400   500   600
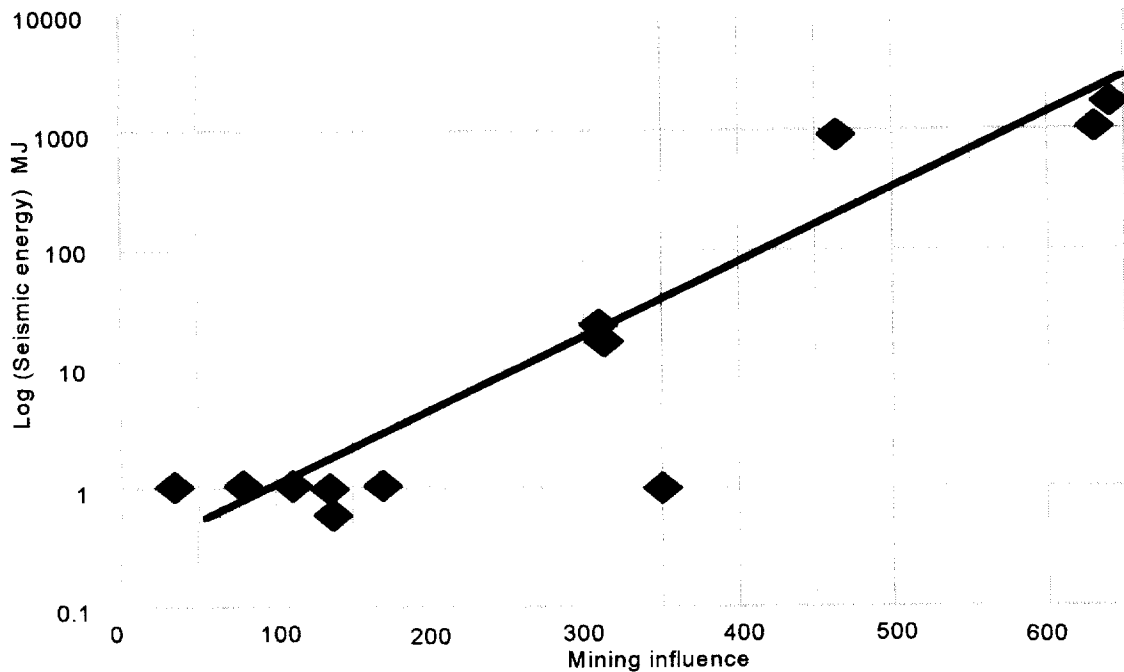
Mining influence

Figure 4.22 The above may be represented on a log normal plot which shows a linear relationship between fault seismicity and mining influence.

Expert system development

Current progress in remnant and special areas analysis was recently discussed with Messrs van der Heever and Webber. Both have developed expert systems providing a systematic, mainly empirical method for assessing remnant stability and mineability. Included in the assessment are a number of practical mining considerations such as shape and size, mining direction, access, panel length and remnant history. Simple seismic statistics, coverage, event size & frequency are included as well as geological structures and proximity to vulnerable excavations. Rough indications of stress, k-ratio, ERR & ESS are included in a simple form.

These expert systems provide a systematic analysis tool which is easy to use for the non expert and should be pursued further.

5. IMPROVED SEISMIC SOFTWARE AND TECHNIQUES

Seismic software development under this project has concentrated on automatic relative location of seismic events by cross-correlating seismic waveforms. The work was done under partly under contract during 1993 and 1994 and in-house during 1995. The bulk of the work is described by the two papers that are attached in the appendix. We summarise some of the highlights of these papers and also discuss recent work.

Our automatic relative locations substantially improve the relative location accuracy of groups, or families, of events with similar waveforms, by a factor of at least two-fold. This improvement would only be achieved conventionally by increasing the geophone density many-fold, a very expensive alternative.

Seismologists usually select a master event that is considered to be both well located, similar to other events and also with a very good signal-to-noise ratio. All other events with similar waveforms are then located with respect to the master event. We have developed and implemented a new and more universal concept in which each member of the family is considered to be a master event to each other member that is sufficiently similar. Within the location procedure, the location of each event is then adjusted according to the arrival-time differences with respect to each other member. We assume that the group as a whole does not move. Families of over 100 events have been identified.

A robust method for studying the spatial distribution of events is by Principal Component Analysis (PCA). We postulate that all events in each family of events locate on one or more parallel planes. We identify this plane either from triangles set up from all sets of three events or from vectors from each event to its successor in the family : the two methods give similar results. Using PCA, we have found families of events that are either face-parallel or associated with geological structures.

The procedure has only been successful for some 50% or fewer of events that can be located manually. Events that have not been located by this method therefore can often still be located manually or by other automatic methods.

Some software development is still required to handle additional events soon after they are recorded. In addition, the method has only been applied to a few PSS data-sets and we are planning additional interpretation within other project areas, such as preconditioning, stabilizing pillars and bracket pillars. Application to ISS data would only be possible if we could access ISS waveform and arrival-time data directly.

6. PUBLICATIONS

Most of the work done under this project is described in a number of papers and reports. These are attached in appendices for reference, though some are still in draft form awaiting publication.

Johnson, R. A.   *Literature review on mining at Ultra-depth and in highly stressed areas.*   CSIR Research report , 1994.

Johnson, R. A.   *Summary and assessment of questionnaire on mining at Ultra-depth and in highly stressed areas.*   CSIR Research report , 1994.

Spearing, A. J. S. *A possible stoping method and support system for tabular gold mining at ultra-depth.* , PhD Thesis, Poland, 1993.

Milev, A. M., Spottiswoode, S. M. & Stewart, R. D. *Automatic location of seismic event doublets by cross correlation criteria.* In Print - Bulletin of Seismological soc. of America, 1995.

Spottiswoode, S. M. & Milev, A. M. *Planes of location in mine induced seismic clusters.* Presented for publication in special volume of techtonophysics on XXI IUGG General assembly, 1995.

Johnson, R. A. *The Influence of Limited Backfill Confinement on Quartzite Material in the Post-failure Regime.* Paper in preparation, 1995.

Schweitzer, J. K. & Johnson, R. A. *Geotechnical classification of deep and ultra-deep Witwatersrand mining areas.* Paper in preparation, 1995.

Johnson, R. A. & Schweitzer, J. K. *Mining at Ultra-Depth: evaluation of alternatives.* Paper in preparation, 1995.

7. POTENTIAL APPLICATION AREAS

Work completed above and suited to application is detailed. Some areas holding promise are also detailed, however in these cases indications of additional work are also given.

Geotechnical areas classification.

Anticipated mining conditions at depths between 3000 and 5000m have been investigated and are given in detail in this report. These include energy release rate (ERR), stope closure rates, face area stresses and excess shear stress values. Considerable information on the geotechnical environment of orebodies potentially mined at ultra-depth have been collected, much in a database form. This information include reef information such as channel width and grade; hangingwall and footwall composition and associated properties; fault and dyke distribution and projected future production trends with depth. These provide essential information for future mine layout planning and assessment.

Pillar & backfill combinations.

Laboratory work has been carried out to quantify the post-failure behaviour of brittle quartzite alone as well as with the confining effects of backfill. This work is in anticipation of the use of crush pillars and backfill as a useful support medium and mining method for application at ultra-depth.

Alternative mining methods and layouts.

Several new mine layouts and approaches are proposed for ultra-depth conditions indicated in a geotechnical classification. New regional and local layouts and mining methods are described that provide increased worker safety at ultra-depth. These offer significantly reduced ERR, increased extraction, reduced stope closure and face stress compared to the best methods currently employed.

Remnant stability.

A detailed assessment of remnant stability by back analysing a number of problematic remnants has yielded disappointing results.

PCA & HRRL improved seismic techniques.

Seismic software enhancements offer substantially improved locations and event classification. This has significant potential in advance identification of hazardous geological features and will be of benefit to ultra deep level mining.

8. FURTHER WORK

Much of the work carried out in this project formed part of a longer term investigation into the needs of the industry to carry out mining at ultra-depth. As such, many of the concepts and ideas which hold promise still require additional work in order to be refined or proven. This indicated future work is set out below in three sections below.

8.1 Ultra-deep mining

Geotechnical Areas - Future work

Recently, it has been confirmed that geological characteristics, such as rock-type, influence the rock mass behaviour around excavations, e.g. the closure rate or the attitude of the mining induced stress fracturing (Roberts, personal communication, 1994). However, our review reveals that the quantification of primary and secondary geological features of rock engineering significance has only commenced. It is recommended that these features receive more attention in the future, and that the information is continuously evaluated in a multidisciplinary team consisting of rock engineers and geologists.

A detailed review of the various fault and dyke populations, and associated joint characteristics, as observed in the regions to be mined at ultra-depth is beyond the scope of this study. However, examination of the literature (Antrobus, 1986; Antrobus et al., 1986; Engelbrecht et al., 1986; Minter et al., 1986; Tucker and Viljoen, 1986; Tweedie, 1986; Killick and Roering, 1994; McCarthy, 1994; Vermaakt and Chunnett, 1994; Berlenbach, 1995) reveals that fault and dyke characteristics and

attitudes differ within the various Goldfields. Frequency and extent of faulting impact on mine layout, on bracket pillar design and are key design parameters for future ultra-deep mining.

Jointing is closely linked to the various fault and dyke populations and it is anticipated that joint characteristics and attitudes will also differ from goldfield to goldfield. This needs to be confirmed through future investigations.

The interpretation of the various structural settings is complicated due to the frequent reactivation of the various fault and dyke planes (e.g. Berlenbach, 1995), resulting in a complex structural setting. The rock engineering significance of different fault rock types (e.g. Roering et al., 1991) also needs further attention. Different fault rocks could possess distinct slip proneness.

The Witwatersrand rocks were, on a number of occasions, intruded by dykes with varying textures and compositions. Compositions vary from basaltic to rhyolitic, which is also reflected in varying competencies of the various intrusive rocks. Future work could consider the potential link between the texture/composition of the dykes and their rock engineering properties. Establishment of such a link would enhance the prediction of dyke behaviour at ultra depth.

A combination of the various geological disciplines, in conjunction with rock engineering, enables the projection of the various rock types, and their associated features (such as rolls; rock engineering properties) into the unknown. Proximal/distal relationships are similarly predictable into the unmined (van Niekerk et al., 1990, 1994). Distinct footwall, but also hangingwall, strata, and the transitions between these, can be related to distinct reef geometries, to depths exceeding 5 km. Seismic surveys and other geophysical techniques, in addition, enable the prediction of geological discontinuities on a local and regional scale. These available prediction and survey techniques need to be incorporated into the mine planning function.

Crush pillars - further work

This work has led to several significant conclusions, however further work is necessary to apply them in practise. Underground trials of pillar/backfill combinations are essential to translate the laboratory results to *in situ* conditions in order to account for scale effects.

No results are available on the stress distribution in the crushed samples. Examination of the samples would indicate highest stresses at the confined core. This could be verified with additional laboratory and/or numerical modelling.

Additional work is necessary to gain a better understanding of crush pillar behaviour at high strains and on the influence of induced high stresses resulting from confined pillars on the immediate hangingwall and footwall strata. It is important to confirm that there is no potential for crush pillars

to induce a sudden foundation failure at high stress. This work can be carried out by numerical and or laboratory modelling.

The influence of shape on pillar performance is not well known. Laboratory work is usually carried out with cylindrical samples, with rectangular or square shapes underground. A small laboratory program comparing shapes would be useful to translate results to different shapes.

Alternative layout design - further work

Little is known about several important design factors for taking mining to ultra-depth and these require investigation.

The *in situ* state of stress and k-ratio at great depth are largely speculative, and are vital to layout design and stability. In the first instance available data across the industry should be collated and evaluated, preferably in a geographic information system (GIS). Where possible such data should be extrapolated to greater depths. Where necessary, such data should be supplemented by additional measurements.

Similarly, engineering properties of the rock such as strength, elastic and inelastic rock properties are unknown or known only as general averages. Such information should be collated in a scientific fashion including means and standard deviations for different reefs and adjacent strata.

Detailed evaluation of a number of potential mine layouts and mining methods for ultra-deep conditions including:

- safety and risk assessment parameters,

- economic viability,

- productivity potential & practical considerations,

- environmental assessment,

- guidelines for the formulation of appropriate codes of practise.

Future research needs - AJSS

Areas were identified in the report that needed additional research :-

Differential velocity measurements must be made (during seismic events) between the hangingwall and the footwall to determine an optimum rapid yield velocity for a RYHP and the need for any rebound facility in the prop. The need for rebound will also depend on the frequency of the differential movement.

Drilling techniques and equipment must be designed to allow for drilling holes in highly stressed rock and the effective charging and detonation of these holes. Advances in longhole drilling have been made in preconditioning drilling which would be of assistance.

The reliability of the rockburst management strategy - Alert, Alarm, Scram- needs to be tested in the field for a period of time to establish a data base of seismic event precursors (if possible).

A design code for bracket pillars needs to be established based on local geology, practical experience in the field, inelastic computer studies and seismic data. This could also require fairly extensive in situ stress measurements near geological features and rock property specimen tests.

The performance of concrete pillars at high stress needs to be investigated with particular reference to whether violent foundation type failure can in fact occur (it appears not from the computer based study).

Dynamic inelastic rock mechanics computer codes need to be calibrated and refined using back analyses to assist in the longer term mine layout and support design in a specific mining area.

The feasibility of re-establishing a stope panel after a major fall as described in principal (using shutters and cementitious foam) needs to be tested in the field.

8.2 Remnant stability.

Remnant back analyses should be re-done as larger seismic datasets become available. In cases where hazardous remnants are being mined, dedicated or improved local seismic monitoring is warranted. In particular, S/P ratio and b-value appear to give a measure of change in seismicity away from remnants and onto adjacent geological features. This would need to be confirmed through additional case studies.

Remnant expert systems provide a good systematic was of approaching remnant mining, and warrant further assessment and development

8.3 Seismic software.

Several modifications to the methods are currently being tested, and these should be validated against available data. Some changes to papers to be made as suggested by referees.

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10. ACKNOWLEDGEMENTS