SAFETY IN MINES RESEARCH ADVISORY COMMITTEE

SIMRAC

DRAFT

Final Project Report

Title: **REVIEW OF COMPLETED SIMRAC PROJECTS AT CSIR DIVISION OF MINING TECHNOLOGY 1993 - 1995**

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1. INTRODUCTION

The improvement of the wellbeing of workers employed in the mining industry is the goal of research sponsored by SIMRAC (the Safety in Mines Research Advisory Committee). However, research has little value unless the findings are successfully implemented on the mines. The effective transfer of technology is an important challenge facing both industry and researchers.

Since the research programme commenced in 1993, many voluminous technical reports have been produced. It is unrealistic to expect senior mine management to study these reports and to identify the findings which can be implemented on their mines. This report was commissioned to overcome this difficulty.

Projects conducted by the Rock Engineering Programme, CSIR Division of Mining Technology and completed prior to 1996 have been reviewed and findings that can be implemented identified. As an aid to planning future research, areas that require further work have been identified, as well as those areas which are unlikely to be viable, or which should be discontinued.

2 GAP024: Develop guidelines for the design of pillar systems for shallow and intermediate depth, tabular, hard rock mines and provide a methodology for assessing hangingwall stability and support requirements for the panels between pillars.

The GAP024 project commenced in 1993 and was initially planned to research pillar stability over a three year period. The project scope was changed in 1994 to include an evaluation of the stability of panels between pillars and the project duration increased. Nevertheless, the work was completed within the original budget through a reallocation of project resources.

2.1 Outputs which can be implemented

2.1.1 Properties of Bushveld Complex rocks

Initial work within this research area focused on establishing a fundamental understanding of the rock mass characteristics of the Bushveld Complex rock types. A laboratory testing programme conducted in collaboration with Witwatersrand University investigated the scale effect on the rock types of the Merensky reef horizon. This work indicated that the strength of intact samples levelled off at approximately 100 -150 mm sample size, indicating that it may be possible to derive the intact rock mass strength of these rock types within the limitations of laboratory test procedures, unlike work conducted in coal where extrapolation outside of the laboratory test data is required. The establishment of the intact rock mass strength was the first step in the procedure for establishing the overall rock mass strength. The laboratory test programme also investigated the influence of a friction reducer between the sample and the loading platens on the response of the test material. This work indicated a reduction in strength of up to 50 % and a change in the failure mode from scaling and shear failure to axial splitting. The reduction in the rock strength is significant with regard to the in situ contact condition between the pillar, the hangingwall, and footwall country rock.

2.1.2 In situ pillar performance

In situ monitoring of pillars was conducted with the collaboration of Impala Platinum mines. This work involved the direct monitoring of several crush / yield pillars and the monitoring of the adjacent general rock mass to determine the system behaviour. Preliminary results in this area indicated the importance of the geotechnical structure of the pillar on its load bearing capacity. This indicates that the geotechnical structure is a critical parameter when downgrading the pillar rock mass to determine its load bearing capacity. Observations also indicated the importance of the stability of the pillar foundation, especially in areas with a weak parting within the footwall rock mass.

2.1.3 Panel strata control

The strata control aspect of the project, which commenced in 1994, focused on the importance of the geotechnical structure of the hangingwall rock mass on the stability of the span between pillars. The focus of the work was on the definition of critical mining spans for different geotechnical areas, by the establishment of instrumentation sites and an evaluation of the potentially unstable ground conditions, and, thus, support requirements. During the project period the first site was established at RPM Union Section in what was considered to be "poor" ground conditions.

Several characteristic fall of ground geometries were defined for this geotechnical environment. This analysis allowed the definition of problematic joint configurations, and, in conjunction with relatively simple geotechnical mapping of the stope pre-development, enabled the definition of areas of potential instability within the stope panels. This technique indicated the need for the implementation of upgraded support strategies in the defined areas, and may have merit as a hazard identification technique in other mining environments.

The detailed instrumentation programme which was conducted indicated that for this geotechnical environment (RMR 56) a critical panel span of 30 m should be used as a mining limit. This was based on a measured increase in the hangingwall deformation rate at spans in excess of 30 m and the general observation of the increased frequency of falls of ground. The deformation of the hangingwall strata was primarily associated with the first 4.5 m. This corresponded well with other observations made at Northam Platinum for a similar depth of stoping. In this stoping environment support recommendations were for fairly high areal coverage and sufficient capacity to support to the unstable height of 4.5 m. Of significance for this area was the measurement of a large proportion of stope closure being associated with the stope footwall to a depth of 9 metres. This footwall deformation often resulted in the failure of the support units with associated subsequent hangingwall instability. A significant recommendation from this work has been the necessity for support units to have sufficient yield capability in order to accommodate the anticipated footwall movement and, thus, prevent premature failure. While it is considered that a detailed understanding of this geotechnical environment has been obtained, it is important to derive a methodology for the definition of critical mining spans in other geotechnical areas.

2.1.4 Footwall heave / pillar punching

The measurements and observation of footwall heave at several sites across the Bushveld Complex indicate the importance of this aspect of the pillar system on the overall behaviour of the system. Thus, within the new project definition, this aspect of the pillar system design is being addressed.

2.2 Areas which require further work

In general the initial period of this project has given the researchers a greater fundamental understanding of the rock mass behaviour associated with the design of pillar systems. It is now considered important that this work focus on deriving practical design tools to aid the industry in the safe design of pillar systems.

2.2.1 Pillar design methodology

An estimation of the scaling procedure for intact rock has been determined. However, it is now important to establish the relative influence of factors such as geotechnical structure, contact hanging- and foortwall condition, local loading profile and geometry on the strength of the pillar structure. In addition, it is considered important to analyse these input parameters on the basis of their variability and, thus, establish a probability of the stability of the pillar structure.

2.2.2 Loading system

In order to determine the pillar capacity an understanding of the pillar demand must be established for the differing environments in which pillars are used. An important aspect is the necessity for barrier pillars to limit stope spans and thus reduce the influence of increasing span on the pillar loading history.

2.2.3 Strata control

The monitoring of underground strata control sites may enable the determination of a critical mining span for a specified geotechnical environment, if the mining configuration allows extraction to the point of the onset of instability. However, limited sites of this nature are available and it is proposed that an industry survey of the current practices, with regard to panel span and internal support systems, be conducted in order to establish an empirical data base. This may allow the development of design charts to determine the influence of the geotechnical environment and the internal support on the maximum stable span between pillars, especially where the monitoring sites are established at the more rigid design points. An important aspect of this design concept is the establishment of a suitable rock mass classification system.

2.2.4 Foundation stability

An important aspect of the stability of the pillar systems is their potential for pillar punching and associate footwall heave. This would be a new aspect of the project which has important implications for the optimisation of the pillar capacity, as well as the characteristics of the internal panel support in order to accommodate the anticipated footwall heave.

2.3 Areas which are unlikely to be viable

No areas identified as not likely to be viable.

2.4 Areas which should be discontinued

No areas identified.

3 GAP026: Strata control in tunnels and an evaluation of support units and systems currently used with a view to improving the effectiveness of support, stability and safety of tunnels.

GAP026 was initially planned to commence in 1993 as a three year project to examine problems associated with tunnels in the Bushveld Complex. However, at the end of 1993 the project was re-scoped to examine problems associated with tunnels in both gold and platinum mines, as well as and to conduct a laboratory testing programme to simulate the in situ performance of typical current support systems. These additional aspects of the project were conducted within the original budget with an allowance for the continuation of the project beyond the three year period. Thus results from the project were preliminary in nature.

3.1 Outputs which can be implemented

3.1.1 Tunnel support design methodology

The initial work within the project area indicated the need within the mining industry for a rational design methodology for tunnel support. This was particularly true in problematic ground conditions, such as highly jointed and altered rock masses and high stress and dynamic environments. Thus by the end of the initial project period (1995) a conceptual design methodology had been formulated which was based on the systematic interaction of support units to create a reinforced rock mass shell or arch within the excavation peripheral rock mass. This is fundamental to, and the basis of, most empirical design methodologies for support systems. The methodology focuses on the influence of the anchor length and load, within the defined geotechnical structure to derive a support unit spacing to ensure interaction. This methodology, as illustrated in Figure 1, provides an engineering basis to the design of support systems, and a more detailed understanding of the interaction between support unit length , load and spacing in different geotechnical environments.

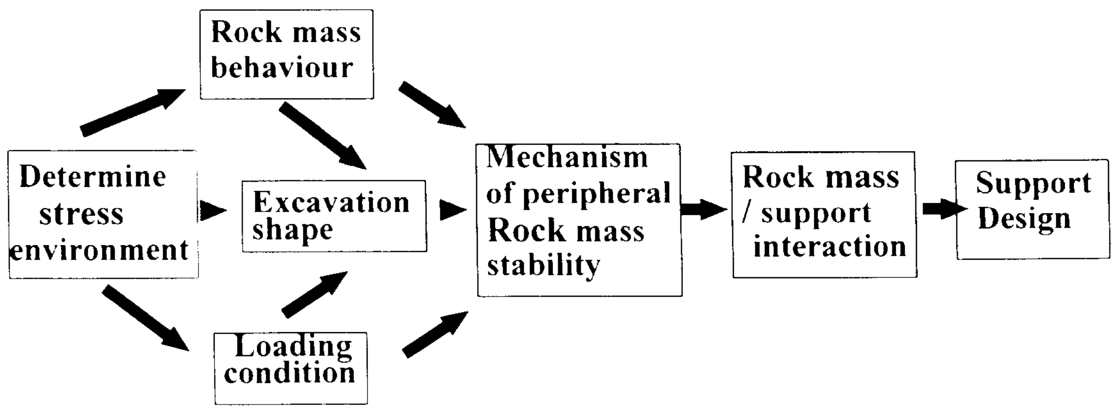

Figure 1. Conceptual design methodology for tunnel support

3.1.2 Influence of support characteristics

Work conducted in collaboration with Vaal Reefs gold mine was focused on an in situ evaluation of long cables on the stability of a tunnel excavation. The main conclusions from this monitoring site was that, for a given geotechnical and excavation environment, the length of anchors had no influence on excavation stability. Instead it was found that the stability was more related to the density of anchors, and that the length of the untensioned grouted cables were in excess of the main fracture zone development, which resulted in no further interaction of the support units, whereas a higher density of anchors would have resulted in increased interaction and thus improved stability. This mechanism is supported by the conceptual design methodology indicated in Figure 1 above. Observations at this site also indicated a significant amount of shear, particularly within the tunnel hangingwall rock mass which was associated with bedding planes.

3.1.3 Laboratory simulation of in situ support loading

The mechanism of rock mass shear for the failure of support units in situ was also noted on further site visits and reports from mining operations. A series of laboratory tests was thus initiated in order to evaluate the relative performance of typical rock bolts under static and dynamic shear loading, Figure 2.

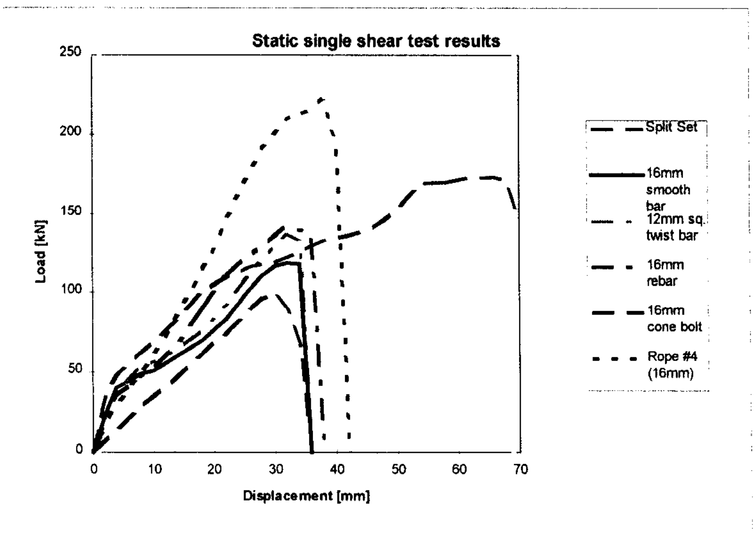

Figure 2. Static shear test results for typical tendon supports.

In general it was concluded that the more ductile and yielding support systems had a higher shear capacity and therefore should be considered for installation in areas where it is anticipated that shear within the rock mass could occur, such as in overstoping of bedded strata or dynamic environments.

3.2 Areas which require further work

The research conducted over the period of the GAP026 project gave an insight into the problems associated with tunnel excavations across the gold and platinum mining industry. However limited implementable outputs were derived due to the fragmented nature of the research and changes in research focus. Of significance was the importance of shear deformation within the rock mass and the relative capacities of the support systems, with respect to the formulation of a conceptual design methodology for the engineering of tunnel support systems. This has resulted in a more focused research strategy within a defined framework of the proposed design methodology. The following areas require further investigation.

3.2.1 Rock mass behaviour

It is considered important to determine the structure of the rock mass around the excavation, particularly for tunnels in overstressed ground, the mechanisms of rock mass deformation and the induced loading conditions on the support systems. This work is being addressed by the establishment of underground sites and re-analysis of previous case studies.

3.2.2 Rock mass / support interaction

Investigations are being conducted into the interaction between support units and the rock mass, with particular attention to the influence of the rock mass structure, support load, length and spacing on the extent of support interaction with the rock mass. The initial work in this area is being verified by analyses of case studies. However, it is considered that in situ experimental work be conducted in order to verify these concepts.

3.2.3 Support capacity

Analysis of rock mass behaviour, and rock mass / support interaction will give an indication of the demand on the support system due to the rock mass deformation. It is important that a full understanding of the capacity of the support system be determined under the anticipated loading mechanisms, i.e. quasistatic, dynamic, axial and shear. Work in this area is currently being based on site visits to areas where support systems have failed in order to gain insight into the failure mechanisms in situ.

3.3 Areas which are unlikely to be viable

No areas identified as unlikely to be viable.

3.4 Areas which should be discontinued

No areas identified.

4 GAP027: Rock mass condition, behaviour and seismicity in mines of the Bushveld Igneous Complex

The GAP027 project was initiated in 1993 in order to obtain an overall view of the rock mass environment and design methodologies for the platinum mines of the Bushveld Complex.

4.1 Outputs which can be implemented

4.1.1 Improved understanding of the geology of the Bushveld Complex

An overview of the geology of this district indicated the importance of geotechnical parameters for rock mechanics design considerations. The highly variable nature of the rock strength properties, the geotechnical parameters and the stress environment indicate the importance of defining these on a local scale for the application of correct design procedures. With regard to the variability of the rock strength parameters, a rock properties data base was initiated to facilitate the assessment of the variability in the rock parameters for design purposes and the derivation of probabilities of system stability.

4.1.2 Geotechnical structure

A joint mapping programme across the platinum mines indicated that the principle joint orientations were associated with the strike of the ore body and the major geological features of the district. However, when abnormal joint orientations were picked up in primary tunnel development these were often indicative of the presence of pot holes on the reef horizon. Thus the mapping of jointing associated with development may serve as a tool for the identification of pothole structures and the generally associated poor ground conditions in their vicinity.

4.1.3 Current design methodologies

A survey of the current pillar design procedures indicated that the use of empirically derived design procedures generally catered well for the majority of the rock mass environments. Concern was, however, expressed that these procedures, principally based on coal mining experience, would not adapt well to the high degree of variability in the rock mass parameters of the Bushveld Complex. The potential, therefore, exists for an increased probability of failure of the pillar systems when abnormal geotechnical conditions are experienced. It was, thus, considered that there was a need for a rational design procedure to cater for the variability in design parameters.

4.1.4 Seismicity

A major proportion of the work was spent on an initial analysis of the seismicity associated with the mining operations of the platinum mines as compared to the gold mining environment. Work was initially based on GENTEL data from RPM Rustenburg and Impala mines. This work indicated a high degree of variability in seismicity between the two mining districts and within the individual mines themselves. This difference was considered to be a function primarily of the different geotechnical parameters, as well as the different mining layouts. The presence of weak geotechnical structures, either within the reef plane, or in the immediately adjacent country rock, is considered to result in a softer rock mass environment with less seismic and rockburst potential than when compared to a more competent rock mass structure. The design of the pillar system may also influence the occurrence and severity of seismicity within a defined geotechnical environment.

A more detailed seismic analysis was conducted utilising a Portable Seismic System (PSS). This work indicated that seismicity, for the investigated geotechnical environment, generally occurred along mining abutments and established pillar lines. Of interest was the predominance of seismicity on the strike abutments of the up dip panels, as opposed to the mining face. This intensity of seismicity along the abutments is considered to be due to the dominant jointing being sub-parallel to a local fault.

4.2 Areas which require further work

In general this project provided an overview of the rock mass parameters of the Bushveld Complex with reference to their use in design procedures. Of significance is the high degree of variability of these parameters across the region and thus the necessity to consider individual parameters in design procedures; as well as the importance of the definition of different geotechnical areas for specific design applications to ensure safe operating practices. These outputs also identify the importance of an understanding of the role of geotechnical structure in the analysis and design of the mining layouts and the seismic potential of the areas of the Bushveld Complex. However, the following aspects require further investigation.

4.2.1 Definition of geotechnical areas

The rock mass response to mining can differ considerably due to the variability in the rock mass of the Bushveld Complex. It is therefore important to establish the relationships between significant rock mass parameters and the anticipated response to mining in order to implement the most suitable rock mechanics design strategy.

4.2.2 Seismicity

Seismicity in the Bushveld Complex is highly variable, probably due to the variability of the rock mass environment. As mining in the Bushveld Complex becomes more extensive at current depth, and deeper ore reserves are opened up, so the incidence of seismicity is anticipated to increase. A determination of the mechanisms of seismicity in the Bushveld Complex will become increasingly important.

4.2.3 Stress environment

The stress measurements within the Bushveld Complex have indicated a wide range in stress values, even within very limited distances. Thus, in order to understand how this will affect rock mechanics strategies, it is important to determine an understanding of the stress environment of the mining district in order to anticipate and implement suitable support systems.

4.2.4 Rock mass behaviour

South African rock mechanics research has principally been based on the understanding of the behaviour of rock at great depth, and therefore the principle focus has been on the modes of rock failure and the development of the fracture zone around deep level excavations. Areas of research and laboratory testing, with regard to the rock mass behaviour, have thus been focused on intact rock properties. It is considered that a far more detailed understanding and knowledge of the behaviour of discontinuous rock masses should be established, particularly for the design of excavations and structures in shallow and intermediate depth mines, but also for the behaviour of the fractured rock around deep level excavations. In both situations it will be important to quantify the effect of in situ stresses on the working areas.

4.3 Areas which are unlikely to be viable

No areas identified as unlikely to be viable.

4.4 Areas which should be discontinued

No areas identified.

5 GAP 029: Develop a quantitative understanding of rockmass behaviour near excavations in deep mines

5.1 Outputs which can be implemented

5.1.1 Analysis of elastodynamic behaviour

The computer code WAVE has been developed to a useable degree which allows elastodynamic interactions between orthogonally oriented faults and stopes to be analysed in both two and three dimensions. Special features of WAVE allow the simulation of dynamic fault slip and simple tabular mining outlines. Numerical studies using WAVE have shown that particle velocities generated by slip on a simulated fault are in broad agreement with established correlations between particle velocities and source distances. For example, application of WAVE to simplified mining problems has shown that backfill can be effective in reducing relative closure velocities between the hangingwall and the footwall of stopes, and that parting planes can trap seismic waves in the hangingwall region resulting in increased potential for the disintegration of the hangingwall. Conditions for the triggering of a large fault slip event by a small precursory event have also been investigated. Photoelastic studies of wave propagation in plates have confirmed the validity of numerical results computed with the WAVE code.

5.1.2 Simulation of stope fracture processes

The computer code DIGS has been extended to accommodate the solution of large numbers of interacting cracks in two dimensions and initial work has been started to allow the analysis of multiple material problems and three dimensional interacting crack problems.

5.1.3 Construction of triaxial test rig

A test rig for performing physical modelling experiments on triaxially loaded samples has been constructed and preliminary rectangular punch loading tests have been performed. This configuration affords a better representation of actual pillar loading conditions and failure patterns than is achieved by means of circular punch tests.

5.2 Areas which require further work

5.2.1 Boundary element elastodynamic analysis tools

The causes of numerical instability in the computer code TWO4D, which is based on the elastodynamic boundary element method, have been identified and methods to reduce or eliminate the instabilities have been implemented. The cause appears to have been that the boundary element method is generally difficult to apply to the analysis of elastodynamic problems in three dimensions. Thus further work is required to assess the general viability of elastodynamic boundary element methods in the simulation of large scale seismic wave propagation.

5.2.2 Studies of rock failure micromechanics

Studies of fundamental rock failure mechanisms have shown that the grain shape can affect the nature of rock failure strongly in terms of rapid load shedding or plastic yielding. This provides a basis for relating the fabric of different rock types to their strength and brittleness. It is important, however, to investigate time dependent micromechanical creep processes to characterize the differences in the seismic response of different geotechnical regions.

5.2.3 Studies of stope scale fracture mechanisms

Pre-existing rock discontinuities, such as parting planes or weak joints, have been shown to play an important role in the formation of extension fracture patterns near openings. More detailed studies of geological and rock strength influences on the formation of fractures near stopes are required together with comparisons to underground observations of fracturing. A survey has been carried out on the effect of geological structures on the pre-existing stress state in different mining districts and the potential effect of this stress state on rock failure analysis.

5.2.4 Blast induced fracture propagation

The role of blasting in promoting fracturing around tunnels has been analysed. It was found that the blast gases can enhance the formation of additional fractures. However, further investigations of the mechanisms of blast assisted fracture propagation are necessary, as well as studies of the interaction of blast processes with stope and tunnel fracturing as a means to control the stability of these excavations.

5.2.5 Time dependent creep and seismic stress transfer processes

Physical observations of slow creep-like stope closure rates have been analysed using a viscoelastic model of a simple tabular excavation with good correspondence being achieved. Studies to quantify creep behaviour on rock joints have been initiated. Time-dependent creep on discontinuities should be included in numerical analysis tools to facilitate the simulation of stope closure rates and the modelling of seismic recurrence effects. Fracture growth in three dimensions should be investigated in addition to fundamental creep-like deformations that occur on mining induced or pre-existing discontinuities. The results of this work could assist in the formulation of a computer code to simulate the time dependent fracture zone formation as mining progresses. This would enable design studies to be carried out to determine the effect of face advance rate on the cyclicity and severity of seismic activity in different geotechnical environments, as well as to evaluate the efficacy of support or other engineering strategies that are proposed to control the stability of the stope fracture zone. Consideration should also be given to the possibility of generating optimal mine layout sequences, that would automatically satisfy appropriate energy release constraints or other layout evaluation criteria.

5.2.6 Mechanics of the interaction of seismic waves with the stope fracture zone

It is recommended that further work should be carried out to study the interaction of seismic waves with stope fracture zone discontinuities in order to understand the mechanics of hangingwall stability. In addition, experimental and numerical investigations of blast assisted dynamic fracture growth processes should be carried out. In particular, appropriate dynamic constitutive representations of pre-existing discontinuities should be quantified.

5.3 Areas which are unlikely to be viable

Due to the fundamental nature of the research project, there are no clear areas that in the long term would be unlikely to provide insight into current mine design problems. A balance must be struck between extensive studies of micro-mechanical failure processes and stope scale failure simulation.

5.4 Areas which should be discontinued

No areas identified.

6 GAP030: Preconditioning to reduce the incidence of face bursts in highly stressed faces

6.1 Outputs which can be implemented

Sufficient understanding of the mechanisms of preconditioning exists, and the benefits are so obvious, that a broader introduction of the technique is possible at this stage (outside of the current research arena). However, the actual implementation of either technique is not necessarily trivial and there exists the potential that the incorrect application of the techniques could lead to serious consequences. It is, therefore, recommended that Miningtek establish an implementation team that could identify potential implementation problems and evaluate how best to conduct the process of technology transfer to ensure the proper implementation of preconditioning throughout the mining industry.

6.1.1 Face parallel preconditioning

This technique has been successfully used in the extraction of reef from highly stressed remnants and pillars. A considerable amount of data exists indicating the effectiveness of preconditioning at transferring stress away from the rock mass immediately ahead of the working face. The layout of long, face parallel holes has been optimised (although only for a limited number of research sites) in terms of the hole size and length, positioning and charging of the hole. The integration of this technique into an existing mining procedure is, however, not easily accommodated but may be a necessity in the most potentially hazardous conditions.

6.1.2 Face perpendicular preconditioning

Considerable benefits have already been realised with the use of face perpendicular preconditioning and this is evident in the attitude of the personnel underground. A consistent reduction in rockburst damage is noted in the preconditioned panels when compared to adjacent, conventionally mined panels. Production benefits have also been realised with a significantly improved face advance accompanying the production blast. The resulting cost benefit equates to a stoping cost saving of R60/m^2.

6.1.3 Ground motion monitor

The ground motion monitor was developed in an effort to evaluate ground motions during a rockburst. This area of research was considered to be of such importance that a new SIMRAC project was initiated to investigate the site response to rockbursts (GAP 201). The ground motion monitor was used on several occasions on stope faces to investigate the effects of a face parallel preconditioning blast on the face. This was useful in evaluating deficiencies in the layout for this preconditioning procedure which primarily relates to the long stemming length required to contain the blast.

6.2 Areas which will require further work

6.2.1 Mechanics of preconditioning

The need to provide a proof-of-concept quantification or a direct confirmation, that the front abutment load is, indeed, displaced further ahead of the stope face by the preconditioning blast, has been highlighted. There exists a considerable amount of information on which this concept is based, but there has been no direct measurements of stress or strain evaluations in the area directly influenced by the blast. Indirect evidence of the concept of stress transfer associated with preconditioning is provided by the detailed seismic records which indicate a spatial migration of subsequent microseismicity and the triggering of larger seismic events. Convergence measurements near the stope faces, together with seismic tomographic surveys and numerical modelling also support the benefit of preconditioning. An attempt must now be made to directly measure the changes in the rock mass immediately ahead of the stope face following a preconditioning blast.

The research into the mechanism of preconditioning has been limited to only a few sites and the effects of varying geology (structures and rock type) needs further evaluation. This needs to be considered if the benefits of preconditioning are to be predicted and implementation guidelines are to be drawn up for the industry.

6.2.2 Face parallel preconditioning

The method of face parallel preconditioning has shown to be very effective in reducing the risk of suffering seismic damage while mining in a highly stresses environment, but the detailed results have been obtained from only one environment, namely a Carbon Leader stability pillar. Further work should be carried out in a different environment under the guidance of this project team to evaluate the technique under new conditions. Poor mining conditions (primarily labour related) encountered at the Blyvooruitzicht site, need to be overcome in order to better quantify the effects of this method of preconditioning and allow for the evaluation of its cost implications. Alternative stemming techniques need further research to reduce the length of uncharged holes resulting in inadequate preconditioning along the stope face.

6.2.3 Face perpendicular preconditioning

Although the benefits of the introduction of preconditioning are obvious, a quantification of the effects of preconditioning needs to be completed. To do this methods to rate the effectiveness of preconditioning in various areas are necessary in order to evaluate its applicability in a variety of areas. At this time, the layout of preconditioning holes is based on a limited amount of information obtained from trial holes drilled and blasted on the Carbon Leader Reef at the Blyvooruitzicht site, and the relevance of these results still needs to be evaluated. An optimisation of the layout is necessary to provide the best results with a minimal disruption to the daily routine of workers at the stope face. Evaluation of the technique in other environments will also be required before industry-wide implementation can be considered.

6.2.4 Seismic risk assessment

The area of seismic risk assessment has been investigated and the results to date look promising. Gains in excess of four times (in terms of identifying high risk periods) can be obtained when using a multi-parametric approach to the evaluation. This does become a 'trade-off' between the percentage of production lost at times of high risk with the percentage of potentially damaging events occurring during this time. This evaluation has been limited to the Blyvooruitzicht preconditioning database and needs further evaluation (on other data sets) if the technique is to be used on a mine-wide basis. The potential for integrating preconditioning with a method of risk assessment would truly result in a pro-active approach towards the rockburst problem.

6.3 Areas which are unlikely to be viable

6.3.1 Electromagnetic emissions

It was believed that electro magnetic (EM) emissions could be used as a possible precursor to failure within the rock mass. A study of seismicity emanating from the 17-24W stability pillar at Blyvooruitzicht could not correlate seismicity with EM emissions and this work area was terminated early in the project.

6.4 Areas which should be discontinued

No work that has continued to the end of 1995 should be terminated as the remaining areas of study all show promise.

7 GAP030: Controlled fault slip for safer mining adjacent to geological discontinuities

The original 3-year project proposal (1993 – 1995) had the controlled fault slip (CFS) research combined with the face preconditioning work under the project title: *"Develop preconditioning and controlled fault slip techniques to control rockbursts for safer mining in seismically active areas"*.

During 1993 and 1994 the CFS research concentrated on pumping water onto seismically hazardous fault planes in an attempt to initiate slip on them. At the time, the water injection work investigated two ways of initiating slip:

1. to trigger large seismic events, i.e. to release a potential rockburst as a single controlled seismic event at a pre-determined safe time
2. to perform incremental slip, i.e. to release a potential rockburst as a sequence of small magnitude (non-damaging) seismic events at pre-determined safe times.

Of the two options the incremental slip approach held the higher promise of success. However, by the end of 1994 field experiments showed that water was a nominally successful, but inefficient, means of initiating seismicity (i.e. slip) on faults. An alternative project proposal was formulated for research into low viscosity fluids (i.e. propellants) to be done during 1995 as an alternate means of initiating fault slip. The second project proposal was titled: *"Investigate methods of low viscosity fluid injection to initiate controlled fault slip for safer mining adjacent to geological discontinuities"*.

7.1 Outputs which can be implemented

7.1.1 <u>Water injection work</u>

The Bounded Parallel Plate Model (BPPM) formulation of fluid flow entering a constant aperture crack from a wellbore has been implemented in a simple Visual Basic computer program designed to run under Windows95. The program takes four input parameters (maximum wellbore pressure, number of wellbores, wellbore spacing and critical slip pressure) and then graphs the fault surface pressure distribution and reports on the potential slip event radius associated with the specified critical slip pressure.

InFrEnd1 (or Intelligent Front End: Module 1) was developed to help with the rapid and easy setting up of UDEC data files to simulate fault slip problems. The interface is highly domain specific, dealing with a single mining problem, namely the issue of stoping in the vicinity of a single geological discontinuity. Although the problem type is very specific, the actual geometry that can be developed for simulation is very general. For instance, the fault throw, mining pattern and applied stress sate are entirely open to modification when a problem geometry is generated with InFrEnd1 for subsequent simulation using UDEC. The Bounded Parallel Plate Model described above has been fully implemented in InFrEnd1 in order to accommodate UDEC simulations of single and multiple wellbore fluid injection exercises. The generation of relevant static domain pressures adhering to the BPPM model is fully automated in InFrEnd1.

A video of the pumping system, acquisition/monitoring/control electronics and field procedure of underground pumping trials was put together as a visual record of the stage that the water injection research had reached before it was terminated in 1994.

7.1.2 Propellant injection work

A SIMRAC interim project report was written in 1995 which reviews the literature on the use of propellants in the petroleum industry, and the implications for their use in the CFS project. This document serves as an important departure point if further research into propellant gas injection is required in the future.

An expert consultant in the field of ballistics developed a Vented Borehole Pressurisation Model and produced a report which covers:

- description of a conceptual model of propellant gas injection (from propellant ignition to discharge of gas through ventholes into a crack)
- formulation of equations of motion describing the gas flow and the associated pressure field in a narrow, laterally extended aperture
- preliminary simulations of gas flow from a propellant cartridge using a proprietary package VENTFLO

This document also serves as an important departure point for further research into CFS using propellant gas injection.

Maximum venting pressures at the point of gas injection onto a crack in uniaxially loaded concrete blocks were approximately simulated with VENTFLO.

7.2 Areas which will require further work

7.2.1 Water injection work

Further work into interface design for InFrEnd1 is likely to concentrate on alternative solvers for programs other than UDEC and on graphical operating systems in preference to MS-DOS.

Miningtek's experiments with fluid induced seismicity in the unsaturated rock masses experienced in the underground environment have lead to the following conclusions:

- fluids can be used to induce seismic events; however, large magnitude seismic events are not easily induced in unsaturated natural joint systems

- fluid flow in unsaturated natural joint systems is through distinct channels
- there is little interconnectivity between relatively closely spaced wellbores in systems dominated by the channel flow described above
- for fluid injection to induce seismic events of the required magnitude (M = 0 approx.), uniform pressurisation radii of around 15 metres must be achieved
- the necessary pressurisation radii could not be achieved with water as it is too viscous

So, although water injection into an unsaturated rock mass is capable of inducing micro-seismicity, it is not possible to induce seismic events of sufficient magnitude to dissipate the required amount of energy from a fault surface as water is too viscous to allow the required penetration of the fault surface. However, it is known that seismic slip of the necessary magnitude can be generated by water in a saturated rock mass. Historical seismicity associated with impoundment of dams serve as an example. Very large quantities of water, far greater than can be pumped by conventional underground pumping systems, are required for this. It may, therefore, be possible to saturate the rock mass artificially in specific areas by feeding large quantities of water from underground storage reservoirs into the target faults via purpose drilled boreholes that are collared at the necessary elevation to provide the required pressure due to the head of water in the system, and to effectively saturate the rock mass this way. This approach will require further work.

7.2.2 Propellant injection work

Laboratory experiments with propellants venting gas onto a simulated fault plane in a split-block setup should continue in order to evaluate the effectiveness of gas injection as a means of initiating fault slip. Shortcomings in the initial experiments have lead to improvements in the laboratory setup. These improvements include: a change from cast concrete blocks to the use of rock slabs mounted in an aluminium template, the inclusion of a plenum (combustion) chamber in the propellant cartridge design and the incorporation of a multiple pressure transducer array capable of measuring the gas pressure front and associated radial pressure distribution in the fault plane with distance away form the point of venting. The rock slabs are mounted in an aluminium template on an incline whose angle can be varied by using pre-cut wedges. The experimental design has evolved enough to allow useful sensitivity analyses to be performed in the future. Biaxial and triaxial loading of the split-block setup should also be performed if the uniaxial tests are successful.

The VENTFLO simulation package promises to possess the range and type of simulation capabilities that can be directly useful for further development of the pressurised crack concept. Among its uses would be:

- laboratory testing: to provide physical insight; to allow interpretation of measurements; to guide development of testing and measurement techniques
- borehole cartridge: to allow the design of a full-scale borehole cartridge for field experiments based on propellant and venting characteristics
- dynamic model of pressurisation: to provide a suitable platform for the start of the analysis of gas flow in the fault plane

In order to solve the entire propellant gas injection technique numerically, numerical algorithms need to be created which couple the gas-generator dynamics (output from VENTFLO), the external flowfield in the aperture and the aperture dynamic equations and solve them together. This may be done through the creation of external subroutines linked to the gas-generator code (VENTFLO) and to use the output from this code as source terms for the description of the external flowfield. This non-trivial and important numerical approach needs to still be done.

The above modelling formulation requires validation of the predicted radial pressure distributions of pressure-time histories in the aperture. The split-block laboratory setup is invaluable in this regard and, as mentioned earlier, the experimental design has been improved to yield real-time dynamic measurements of flowfield characteristics in the aperture.

After validation of the concept in the laboratory and numerically, the propellant injection technique needs to be extended to field trials. A borehole propellant cartridge needs to be designed that can provide a pre-programmed pressure pulse amplitude and duration sufficient to induce slip. The military-type propellants used in the laboratory experiments will probably need to be replaced with more effective (higher gas volume generating capability) and user-friendly (non-toxic gas generation) propellants, such as those based on sodium azide, similar to those used in automotive airbags.

7.3 Areas which are unlikely to be viable

7.3.1 Water injection work

The saturation of faults with water from underground storage reservoirs is unlikely to be a viable way of controlling rockbursts. The reason for this is that faults often become seismically hazardous in a relatively short period of time (due to advancing mining operations) and one needs a portable technique that can pump water onto such faults quickly in order to be a practical solution. The establishment of underground reservoirs and the drilling of multiple boreholes to intersect seismically hazardous faults would be too time-consuming and costly.

7.3.2 Propellant injection work

Initial investigations into the use of propellant gases as a means of initiating slip on faults have indicated that low viscosity fluids hold promise in this regard. Further work needs to be done in this direction (as indicated above) before viability of this method as a practical, implementable pro-active rockburst control measure can be assessed

7.4 Areas which should be discontinued

7.4.1 Water injection work

Water is not a viable medium for the practical implementation of CFS by fluid injection. Thus, pumping high pressure water should not be further investigated as an efficient way of ameliorating the rockburst problem that is associated with slip along existing geological features.

7.4.2 Propellant injection work

The work investigating an alternative means of initiating slip on existing geological features by pumping low viscosity fluids (propellants) onto faults should be pursued. This work should not be terminated, as it currently is the only promising way of improving the rockburst hazard associated with slip on faults. Terminating this work without alternative solutions would be detrimental to the mining industry, as a major rockburst problem will simply be ignored.

8 GAP032: Stope and gully support design

The main objectives of this project were to develop a rationale for the design of stope support systems and to develop improved support systems for gullies in both static and dynamic conditions.

8.1 Outputs which can be implemented

8.1.1 Stope support design methodology

Support resistance and energy absorption criteria for rockfalls and rockbursts respectively have been determined for the Ventersdorp Contact Reef, Carbon Leader Reef and the Vaal Reef. These criteria depend upon ejected rock thicknesses during rockfalls and rockbursts and may need to be refined by the rock engineering staff on specific mines exploiting these reefs. The ejection thicknesses, so determined, can be used to evaluate and design stope support systems by means of the stope support design methodology developed as part of the GAP032 project. The methodology relies on knowledge of the performance of various support units and knowledge of the stope closure rates.

Some assumptions are made when dealing with dynamic loading, namely, it is assumed that the maximum velocity reached in any seismic event will not exceed 3 m/s and that the hangingwall closure must be stopped within a distance of 200 mm. A further assumption is that the hangingwall span between support units will remain stable under load. These assumptions may be debatable, but despite this the methodology, for the first time, offers a sound engineering basis for stope support design. The methodology can be used for both face and back-area support design and can be implemented now.

8.1.2 Gully support design criteria

Gully pack performance and foundation stability beneath the gully packs was determined by underground monitoring. The result of this study led to a better understanding of the force-deformation behaviour of gully packs with time, leading to a recommendation for performance characteristics for gully packs under various conditions. This knowledge can be applied now.

Hangingwall fallout thicknesses in gullies have also been determined to establish both the support resistance and energy absorption criteria for gully support. The work concentrated on the Ventersdorp Contact Reef, the Carbon Leader Reef and the Vaal Reef. Gully support criteria have been derived and rockbolting support requirements have been defined to meet these criteria. The method can be used to design support requirements for mines exploiting these reefs, and mines exploiting other reefs provided fallout thicknesses have been determined.

In the case of stope support, design criteria are derived for each reef from the fallout thickness which accounted for 95 % of the rock related fatalities. In the case of gully support, figures of between 90 and 100 % are used. These figures are debatable and individual mines may wish to use lower or higher percentages bearing in mind the need for a factor of safety to cater for uncertainties in design parameters and quality of support installation. The methodologies mentioned above assume a perfectly installed support system in each case. Adjustments upwards for the support resistance and energy absorption requirements to compensate for imperfect installation, resulting in blasting out for example, should be made.

8.2 Areas which require future work

8.2.1 Extension of support design criteria to other reefs

So far the work has been focused on the Ventersdorp Contact Reef, the Carbon Leader Reef and the Vaal Reef. Expansion of the data base to determine criteria for other reefs still have to be done.

8.2.2 Stability of hangingwall between support units

An improved assessment and understanding of the stability of the hangingwall between supports in differing geotechnical environments is required. Questions regarding the effect of area coverage and the effect of non-axial loading of support still have to be answered. The impact of face advance rate and time-dependant behaviour of the rock mass on support design requirements must also be determined. Underground measurements and numerical modelling are also needed to play an important role in determining and analysing the abovementioned effects.

8.2.3 Impediments to the implementation of stope face support systems

Impediments to the successful implementation of stope face support systems, within the various geotechnical areas, need to be investigated.

8.2.4 Elongate performance

Elongates (most of which are timber-based) are being used fairly widely in gold and platinum mines for panel support. These elongates are often used in conjunction with rapid yield hydraulic props but in some cases the pre-stressable and yielding type elongates have replaced the latter, for face area support, in seismically active mines. Energy absorption calculations and limited statistics have revealed that the pre-stressable and yielding varieties of props may be acceptable under seismic conditions, apparently offering both safety and production advantages. Some concern has been expressed, however, that the performance characteristics and consistency of this type of support have not been fully evaluated. A laboratory/underground test procedure, to evaluate both yielding and timber elongate support performance and their applicability in gold and platinum mines is required.

All the abovementioned aspects are currently being addressed in SIMRAC project GAP 330.

8.2.5 Rockburst energy criteria

Current methods for the determination of rockburst energy criteria assume a closure velocity of 3 m/s. Some justification for using this velocity is evident but further investigation is necessary. Rockburst closure velocities are likely to be different for different reefs and for different geotechnical environments on individual reefs. SIMRAC projects GAP201 and GAP330 are addressing these aspects.

8.3 Areas which are unlikely to be viable

No areas identified as unlikely to be viable.

8.4 Areas which should be discontinued

No areas identified.

9 GAP033: Develop improved strategies for mining highly stressed areas

The GAP033 project commenced in 1993 with a primary objective to improve support, layout and seismic monitoring procedures, together with criteria for the extraction of highly stressed areas. The aim of this long-term project is to focus on the extreme high-stress end of the mining spectrum. Such high stress conditions will prevail in proposed ultra-deep mining operations, and are already being experienced in extracting remnants, stabilizing pillars or shaft pillars at more moderate depths. A broad based initial investigation was followed by an industry workshop at which directions for the remainder of the project were set. These were:

- investigation of anticipated mining conditions at ultra-depths;
- classification of geotechnical areas at ultra-depth;
- development of new and improved mining strategies suited to conditions at great depth;
- back analysis of remnant stability with a view to reducing remnant associated problems;
- development of improved seismic techniques.

9.1 Areas which can be implemented

9.1.1 Geotechnical areas classification

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. To this end, considerable information has been gathered and collated in a database. New and proposed ultra-deep mining is relevant to the interests of all the major mining houses and covers all current mining districts. The VCR, Carbon Leader, Main Reef, reefs of the Elsburg and Kimberley successions, Vaal Reef, and the Basal Reef are the major targets. The following information has been compiled for each reef:

- projected future production figures;
- reef properties and geometry including both lateral and vertical variations;
- frequency and characteristics of bedding planes and lithological boundaries;
- rock types and available properties are listed for 100 m into hangingwall and footwall;
- compositional and textural characteristics of faults, dykes and joints.

Geological and geotechnical features impact on the rockmass behaviour and play an important role in identifying appropriate mining strategies, layouts and support to exploit ultra-deep orebodies. A geotechnical classification, which broadly distinguishes "hard" and "soft" environments, and reef hazard rating has been proposed to assist in this process.

9.1.2 Improved regional and local layouts

Most current deep level mining is carried out using a longwall configuration with stabilizing pillars at least 40 m wide and at planned extractions of 80 to 85 %. While such layouts are successfully used on a number of mines at depths exceeding 3000 m, there are significant problems with pillar stability and associated seismicity in some areas. The main criterion used for layout evaluation is energy release rate (ERR), while stope area closure, face stress and pillar stress were also used. In addition, ESS modelling is used. Face area stress relates to ease of mining and 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. These results showed that stabilizing pillar layouts without backfill are unsuitable for mining at greater depths. Stabilizing pillar/backfill combinations are significantly better, having ERR's acceptable to depths of almost 4000 m. The major disadvantages of using stabilizing pillars at depth are their failure potential in "hard" environments, the inflexibility of position which may correspond with high grade areas, their influence on nearby haulages, and the effective sterilisation of over 30 % of the available ore, and decreasing extraction with increasing depth.

Three alternate regional support layouts and several detailed panel configurations for use with these regional layouts are proposed. While some of these new methods are suited to immediate implementation, it is anticipated that they will need to modified or adapted to a particular mine application.

1. The first regional layout, termed multi-pass mining, is suitable for "hard" environments and makes use of concrete and backfill. Significantly 100 % extraction may be achieved with this method. During Phase 1 of this layout, 160 m wide headings are mined with backfill and concrete ribs placed adjacent to the central abutment, which is 160 m wide. This provides a low closure environment in which the concrete cures to optimum strength. Phase 2 of this mining (also using stope filling) involves mining the central 120 m, keeping the face approximately 100 m behind the advance faces, which are mined with two 20 m strike rock 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 can be omitted if mining conditions are difficult, or mined with phase 2 using pre-conditioning.
2. The second new regional layout makes use of 20 m strike stabilizing pillars, and is advocated for "soft" environments. As pillar failure usually takes place in excess of 100 m behind the face, backfill is placed right up to the pillar on the up-dip side of the pillar and 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. This confinement increases the pillar strength and reduces the risk of failure of the pillar system.

3. A third regional layout has been evaluated - the use of concrete dip pillars for scattered mining. Careful sequencing of the mining is used to provide a low closure environment for the concrete to cure. Attention to bracket pillar placement and design will be required in geologically disturbed areas.

ERR values for the multi-pass mining and modified stabilizing pillars methods show an improvement of between 30 and 40 % over the best current method. All the methods show a marked reduction in stope closure compared to current methods, which makes yielding face support more effective.

Three alternative local or "in panel" layouts to be used with these regional layouts are proposed.

1. The crush pillar and backfill panel layout may be used in either a "hard" or "soft" environment with either of the regional layouts. In this layout, 20 m panels are mined, with 2 m by 8 m crush pillars on the down dip side of the strike gullies. More detail on the confining effects of backfill on crush pillars is given in the next section.
2. The second panel layout makes use of short panels (no more than 20 m), 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. Advances in drilling technology make this method viable.
3. The third proposed panel layout has the advantage of being similar to current mining, with extensive stope backfilling supplemented by every 10th 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.

9.1.3 Seismic software enhancement

Seismic software development has concentrated on automatic procedures for relative location of seismic events by cross-correlating seismic waveforms. This process improves the relative location accuracy of groups of events by at least a factor of two. Conventionally, such an improvement could only be achieved by increasing the geophone density many fold (at significant expense). Principal component analysis provides a robust technique for studying the spatial distribution of events and has been used to group families of events associated with geological features or face parallel fractures. This offers significant potential for advance identification of hazardous geological features and will be of benefit to ultra-deep level mining. While this technique is only successful for around 50 % of events, the remaining events can still be located by manual or other automatic techniques. These programs are immediately available for PSS application, and could be implemented on ISS if waveform and other data could be directly accessed.

9.2 Areas which require further work

9.2.1 Pillar confinement

The use of crush pillars has been considered in some detail because they have been proven effective at shallow depths. At ultra-depth such pillars are crushed ahead of the face, eliminating any burst potential. A combination of these proven support elements promises a stiffer and more effective support medium and mining method suited to application at ultra-depth. In addition, these crush pillars counter the problematic effects of very rapid closure rates at ultra-depth and provide increased support at the hazardous gully/face area. As little work has previously been done to quantify the effects of backfill confinement on crush pillars, a program of laboratory and numerical modelling work has been carried out to investigate crush pillar behaviour with a view to incorporating these as part of a mining method at ultra-depth. Results indicate that even limited, unconfined backfill surrounding a pillar results in a forty fold strengthening of a 2:1 width to height ratio crush pillar. Similar results were obtained for different fill heights and pillar aspect ratios. These results motivate further work towards applying backfill reinforced crush pillars in suitable high stress areas as well as in the application of confinement strengthening to pillars more generally.

9.2.2 Remnant stability analysis

Work on the assessment of remnant stability was initially motivated by the high percentage of production available across the industry from remnants, isolated blocks and difficult to mine areas. These percentages range from 20 to over 40 % of production in some areas. However, remnants may be highly stressed even at moderate depths and are often hazardous to mine. In the Free State and Klerksdorp districts in particular, many remnants are located adjacent to faults and dykes or at the intersections of faults and dykes.

A detailed back analysis of 15 remnants including a wide range of modelled and seismic parameters has yielded inconclusive results. Although individual cases showed promising correlation between seismicity and parameters such as the b-value, seismic viscosity and S/P moment ratios, there were, however, contradictory examples in each case. In several cases a reduction in b-value from around one to a half indicated a change in seismicity from the face to adjacent geological features. Similarly, the S/P moment ratios may prove an indication of a remnant shedding load. The major problems experienced while carrying out these back analyses are the lack of resolution of mine wide seismic systems in capturing small events and small data sets associated with most remnants. Thus seismic systems having improved location accuracy and better resolution at lower magnitudes are required to assess the use of b-value, seismic viscosity and S/P moment ratios as a reliable indicator of remnant stability during mining.

9.3 Areas which are unlikely to be viable

No areas identified as unlikely to be viable.

9.4 Areas which should be discontinued

No areas identified.

10 GAP034: Deep mine layout design criteria

10.1 Outputs which can be implemented

10.1.1 Back area caving

Research into caving as a practicable mining method has been completed and situations in which caving may be successfully used have been identified. The high and relatively rapid stress regeneration in the cave material indicates that back area caving provides an efficient and cost effective support in areas suited to its application. Stresses up to 7 MPa have been measured in caved areas. The high stresses regenerated are significant as they indicate that the cave material carries considerable load - in same ways very similar to backfill. The validity of the cave method in tabular deposits is highly dependent on the suitability of the geological conditions. Support requirements in caving need to be "tuned" to local conditions to achieve maximum benefit. A continuous and moderate rate of face advance is also required for successful cave mining.

10.1.2 Concrete pillars

Concrete pillars appear to provide both sufficient regional support as well as reducing the likelihood of foundation failure. In addition, less overall pillar failure and more stable hangingwall is likely in the case of concrete pillars. Modelling of concrete pillars compared to reef pillars shows that the regional benefits of reef pillars are not lost as a result of using concrete pillars. They have been shown to have the same performance as the reef pillars with respect to the aspects of closure and average pillar stress. Moreover they provide more stable hangingwall conditions as a result of reduced punching effect compared to reef pillars. These conclusions, which have been positively supported by *in-situ* tests on a concrete block, should be encouraging to mine management because they imply that decreasing extraction ratios need not be necessary with increasing depth. and that conditions associated with pillars may improve so that foundation failures may be reduced. The requirement for significant initial capital outlay needs however to be balanced against the benefits.

10.1.3 Stabilising pillars

It has been observed that, in a specific region of a mine, the seismic events occurring in the vicinity of a longwall adjacent to a stabilising pillar are associated with lower stress drops than events occurring in a neighbouring longwall which is not protected by a stabilising pillar. Damaging seismic events, however, tend to have higher corresponding stress drops. This is a significant benefit of stabilising pillars and is a positive factor for their continued use.

10.1.4 Bracket pillar design

In answering the fundamental question whether a dyke of a greater stiffness than the host rock leads to stress concentrations when a bracket pillar is used, the following was determined:

1. The effect of the stiffer dyke material is to decrease the stress in the bracket pillar, while the stress in the dyke increases. The dyke is thus acting as a stress concentrator. This stress concentration in dykes has previously not been considered, and has obvious implications for bracket pillar design in that the average stress across a dyke may differ from MINSIM-D type outputs.
2. The maximum ESS in case of stiffer dyke materials is of the order of 10 to 15 MPa greater than normally considered

Work carried out in the Klerksdorp region showed the benefits of mining the ground in the vicinity of geological structures first rather than mining against features after extensive spans have been created. Experience shows that when mining first occurs adjacent to the features, any damaging seismic events are usually far away from the working place and there is a reduction in the number of dyke associated events.

10.1.5 Pillar design guidelines

Preliminary strike and bracket pillars design methodologies have been developed to guide the rock engineer practitioner in the effective designing of such structures.

10.1.6 Backfill

The new backfill rockburst and rockfall accident data confirms the research findings which were published four years earlier. The results show that if the percentage of backfilling is high (i.e. 60-70 %), the rockburst damage is reduced significantly in backfill panels compared to unfilled panels.

10.1.7 Modelling

Recent levelling results have validated the use MINSIM-D for elastic modelling as a first order approximation of regional trends of rock mass effects. In addition, prediction of seismic hazard based on parameters derived from elastic models correlate poorly with actual seismicity. Correlation coefficients of better than 0.5 are seldom obtained. Elastic models, as used so far, should therefore be considered as long term strategic design tools, to compare different layouts or to optimise a given layout.

10.1.8 ESS and ERR criteria and Rockburst Hazard Index

The present use of ERR and ESS as design criteria for mine layouts has been successfully investigated. ESS changes with mining, rather than total ESS are more likely to correlate with seismicity. ESS is best used as a measure of the potential hazard associated with a particular layout rather than as a tool for determining the magnitude of an expected event. Volumetric ESS appears to be an approach which considers more of the rockmass with any mining step and therefore presents a more realistic approach to evaluating the seismic risk of any mine layout. The simple use of normalised mined area relative to a geological feature and considering the direction of mining may also give valuable guidance for evaluating the seismic risk of a failure. These facts should be of use to rock mechanics practitioners and mine planners.

A computer program has been developed which combines increments in the Volume excess shear stress (VESS), excess shear along geological structures (ESS) and energy release rate (ERR) into a "rockburst hazard index" (RHI). This index combines criteria which have shown improved correlation with seismicity (incremental VESS, ESS) and the ERR criterion, which is an indicator of rock conditions. The factors contributing to the hazard of rockbursts, i.e. seismicity and poor rock conditions are, therefore, accounted for in the index. The initial case studies show that the calculated RHI correlates well with expected rockburst hazard and overall level of seismicity.

10.2 Areas which will require further work

10.2.1 Geology database

The results from seismic analyses have shown that different geological structures have significantly different behaviour and that this behaviour is most strongly controlled by the mining layout in their vicinity. A database categorising faults and dykes in various mining districts has been created and is currently being extended further. A number of parameters have been considered, e.g. feature orientation, composition, metamorphism, rock engineering properties, structural/tectonic history, fault rock type, dyke/host rock relationships. The implementation of geological parameters into rock engineering design methodologies is crucial and will become even more important at ultra depth.

10.2.2 Bracket pillars

Hazard discontinuity planes (i.e. fault or dyke) have been interpreted in terms of excess shear stress and design charts for bracket pillars have, as a result, been developed. This charts relate parameters such as span and pillar width for an expected magnitude of event. Before implementation takes place, further calibration and verification needs to be pursued.

10.2.3 Stabilising pillars

Relationships between seismic parameters and numerical modelling results have shown that there is a strong association between the "peak stress change" along the pillar and the incidence of seismic events. It is envisaged that a stress change parameter will be incorporated into an improved design methodology for stabilising pillars. Stress changes have not been considered in the past.

10.2.4 Seismic analysis

An improved method for quantifying the hazard associated with a geological structure based on seismic data is under way and requires further development. This method highlights the variable behaviour of different structures and the importance of mining layouts in controlling the hazard associated with a particular structure.

As a result of a suggestion that intensive seismic monitoring should be used to improve the current understanding of the seismic activity with mining in the vicinity of geological structures, a PSS was installed at Vaal Reefs. A number of bracket pillars being planned for a geologically complex mining area are currently being monitored. Time is needed before a proper analysis can be conducted.

10.2.5 Modelling

Refinement of elastic modelling is now possible (e.g. using MAP3D) by inputting into models not only the real spatial representation of geological features but also their proprieties which may different from those ascribed to the rest of the "rock mass".

10.2.6 Passive tomography

The possible areas of application of seismic tomography for deep mine layout design on South African gold mines are the imaging of dyke structures to determine stress concentrations and the imaging of pillars or other features to determine stress concentrations and fracture densities.

An initial active seismic tomography survey indicates the stress concentrations in a stabilising pillar. This is of significance for looking ahead of mining into the rock mass to identify possible high stress areas which may have high seismic potential. This may be used as a tool by rock mechanics practitioners in order to identify such high stress areas.

10.3 Areas which are unlikely to be viable

10.3.1 Active seismic tomography

The resulting images from the seismic "active" tomography exercise carried out at an ideal site at Blyvooruitzicht showed a high velocity zone (corresponding with a high stress zone) ahead of the advancing face. There was a strong correlation between this high velocity zone and an area of increased seismicity. Although the results were of extreme practical importance, it appears that the technique used may not be applicable to assess more general, less ideal mining layouts. Alternatively, passive tomography which will make use of mine-wide seismic networks could be explored (this would be a long term objective).

10.4 Areas which should be discontinued

For the reasons stated above, it is thought that "active" tomography is not suitable a technique for use in routine rock engineering assessments.

11 GAP102: Improved support design by an increased understanding of the rock mass behaviour around the Ventersdorp Contact Reef

11.1 Outputs which can be implemented

The two main objectives of the GAP102 Project were:

- to develop a conceptual model for rock mass behaviour around VCR stopes,
- to improve safety and reduce production losses due to rockfalls and rockbursts, and
- apply the knowledge gained to the design of efficient support systems for use in VCR stopes.

Both these objectives were achieved and the major findings which can be implemented are summarised below.

11.1.1 Definition of geotechnical areas

The concept of geotechnical areas has been shown to be a valid and useful basis for support design. This concept could be applied to other reefs. A methodology to define primary geotechnical areas on a regional basis has been developed. Maps based on three major footwall and two lava types have been constructed for all mines where VCR deposits are found.

11.1.2 Conceptual model for rockmass behaviour around VCR stopes

The findings from the programme of underground visits were that each geotechnical area is characterised by a distinct fracture pattern. A conceptual model of the rock mass behaviour associated with the mining of the VCR has been proposed. A mechanism that may account for the observed differences in the mining induced stress fracturing appears to be associated with different geotechnical conditions. This knowledge forms a basis for understanding differences of response in different geotechnical areas.

11.1.3 Evaluation of the variation in lava type, strength and deformation properties

A well populated database of rock properties and strain softening parameters for FLAC modelling has been established for rock types associated with the VCR. Over 30 hangingwall and footwall rock samples were collected from the various geotechnical areas and tested. The differences in the properties of the relevant strata, especially between hard (Alberton Porphyry Formation) and soft (Westonaria Porphyry Formation) lavas were quantified.

11.1.4 Analysis of data from fatal accident inquiries

A database incorporating information gathered from the Department of Minerals and Energy (DME) record of fatal accident inquiries from 1990 onwards was developed in conjunction with GAP 032 Project and is being kept up to date. Analysis of this data for the last six years showed that the area mined per fatality for hard lava is significantly less than for soft lava, i.e. the hard lava is, more hazardous than the soft. This result may be due to the fact that, firstly only some areas of the soft lava are reputed to have poor ground conditions, and, secondly, that the block sizes that fall out in the soft lava are generally smaller and thus less dangerous than those of the hard lava. The face area is the major location of fatalities on the VCR. This proportion is higher for the VCR than for most other reefs.

11.1.5 Assessment of the variability in stope closure between geotechnical areas

A detailed monitoring programme was carried out at four sites in different geotechnical areas to determine differences in rock mass behaviour. The measurements and observations made in two different geotechnical areas showed that there are significant differences in closure rates (10 mm/day and 5 mm/day), and the amount of the deformation of the strata in the footwall and hangingwall that contributes to the total closure. It was shown that the amount of closure measured at a point in a stope is a function of the rate of face advance. Where the rate of face advance is high the closure rate, expressed in mm/day, is higher than if the face were advanced at a lower rate. However, if the rate is expressed in mm/m face advance, which is of significance to support design. the rates are substantially different.

Detailed monitoring and analysis of closure measurements carried out in this project have allowed the development of a modification to the support design methodology presented in project GAP032. This modification expresses the closure rate as a function of face advance rate, which should assist rock engineers involved in support design on mines.

11.1.6 New hangingwall bolting and lacing system

Design and testing on surface of a new hangingwall bolting and lacing system has been completed. The system is available for underground evaluation.

11.1.7 Analysis of seismic data with respect to geotechnical variations

Total seismicity was modelled as a function of cumulative seismic moment and number of fatalities compared to the volume of elastic convergence. The latter technique was developed in the course of this project and could be used in other studies. The geotechnical areas with a soft lava hangingwall and quartzite-conglomerate footwall are less active than areas with a hard lava hangingwall and quartzite-conglomerate footwall. Similarly, the geotechnical areas with a soft lava hangingwall and Jeppestown shale footwall are less active than the areas with a soft lava hangingwall and quartzite-conglomerate footwall. The geotechnical areas with a hard lava hangingwall and quartzite-conglomerate footwall, were compared to a hard lava hangingwall with Booysen's shale footwall. No differences in the associated seismicity were found. The variations in the properties of the different types of quartzite forming the footwall at Deelkraal, Elandsrand, Western Deep Levels, South Mine, East Driefontein and Kloof Gold Mines do not appear to influence the level of seismicity.

The total seismicity generated appears to be influenced by mining method. The mining induced seismicity at Elandsrand Gold Mine, where the sequential grid mining method is applied, is less than that recorded in the same geotechnical domain at Western Deep Levels, South Mine where longwall mining incorporating stabilising and bracket pillars is practised. The b-values are also different and show that a greater proportion of the seismic energy at Elandsrand is released by small events as compared to Western Deep Levels where a significantly larger proportion is released by large events.

11.1.8 Analysis of thicknesses of falls of grounds and ejection

The cumulative percentages of rockfall thicknesses in VCR stopes were obtained, the height of 95 % of all fallouts causing fatalities was 1.2 m and 1.8 m for soft and hard lava hangingwalls, respectively. The equivalent figures for rockburst ejection thicknesses for soft and hard lava are 2.1 m and 1.8 m respectively. These figures were used to calculate overall support resistance and energy absorption (for dynamic loading at 3 m/s and to arrest the closure within 0.2 m) design criteria for soft and hard lava hangingwalls. These are:

	Support resistance criteria kN/m^2	Energy absorption criteria kJ/m^2
Soft lava	33.0	37.3
Hard lava	49.5	32.0

11.1.9 Accident database

Based on knowledge and experience gained with the current database, assistance was given to the DME in the designing of their new accident data capture form and database.

11.2 Areas which require further work

11.2.1 Definition of geotechnical areas

Geotechnical areas delineate regions with distinct rock mass behaviour. The distribution of lithologies is extrapolated into the unmined areas, facilitating the prediction of hazardous areas. Further scope exists to characterise the geotechnical areas in more detail. Bedding planes, for example, appear to part more easily in the siliceous quartzites, as opposed to their argillaceous counterparts. Little is also known about the lava flow thicknesses considering individual flows of the soft and hard lava types. It is implied that flow thicknesses associated with the soft lava are less than those of the hard lava, because soft lavas represent low-viscosity flows. However, the behaviour of the delineated footwall and hangingwall partings and the rock mass behaviour in areas of VCR mining with siliceous and argillaceous footwalls should be investigated to obtain additional geotechnical data.

11.2.2 Documentation and modelling of structural features

The detailed documentation and modelling of structural features should be considered. This would facilitate a better understanding of the deformation mechanisms and the interrelationships between the pre-mining state of stress (as the result of paleo-tectonic forces) and mining induced stresses, and the prediction of these features. These studies could be combined with modern geophysical methods (Ground Penetrating Radar or Radiowave Tomography) to map mining induced fracturing and geological structures ahead of mining. Detailed documentation of the frequency and amplitude of bedding parallel faulting will also assist in the identification of the approximate support spacing. Evaluation of the above features will need to consider the different behaviour of faults and dykes with varying orientations to the excavation, and compositions of the structures.

11.2.3 Fracture mechanisms

Inclined holes should be drilled from the stope into the hangingwall and footwall in order to obtain better information about fracture mechanisms. If extensometers are installed into some of these holes, after establishing the position of fractures by means of petroscope observations, it should be possible to obtain further useful information on how the rock mass behaves ahead of the face, including where the rock is failing. The relation between closure rate and face advance rate, and the closure rate and orientation of mining induced stress fractures should be examined.

11.2.4 Accident reporting system

The new accident reporting system will need to be evaluated to ensure that it fulfils its role. The system should be considered to be dynamic with the aim of evolving into an ideal system. Feedback from all affected parties will be invaluable in this process. The collection of ancillary information is one area that requires attention. This refers to information concerning annual production per reef and how much production comes from successive 500 m depth ranges, the number of people at risk in each of the depth ranges for every reef in stopes and tunnels and the area supported by each support system per reef per shaft. If such data were available, a more comprehensive analysis of the data would be possible. For the determination of rockburst and rockfall control criteria for support system design methodology, a limited database of six years was used. The expansion of this database is necessary and could be undertaken in the SIMRAC Project on stope face support systems (GAP 330).

11.2.5 Criteria for stope support design methodology

With respect to the stope support design methodology, the basic assumptions are that support systems should be able to stabilise the hangingwall in 95 % of the cases, when the velocity of ejection during rockburst conditions is 3 m/s and the support yieldability 0.2 m. A further study, on higher or lower percentages of cases requiring stabilising of the hangingwall needs to be undertaken. The rockburst closure velocity is likely to be different within different geotechnical areas, and additional investigation in this area is also necessary. This will be addressed by the SIMRAC project on site response to rockbursts (GAP201) and also by SIMRAC project on stope face support systems (GAP330). There is a need to assess whether the maximum height of 0.2 m, typical of the yieldability of hydraulic props and yielding timber props, is sufficient in terms of the variability between different support systems.

The effect of the rate of face advance on stope closure was investigated and, in order to determine the relationship between closure and average face advance, the stope area was divided into two areas, e.g. the face and back areas. The first 10 m of the area in the face area was assumed to be the face area due to very limited measurements. However, due to lack of information for the back area, further investigation is needed and a more well organised study initiated taking into account the different geotechnical areas.

Quantitative measurement of the velocity and acceleration of the rock surfaces was initiated during this project for only one geotechnical area in Western Deep Level Gold Mine - South Shaft.

The data acquisition and analysis is an ongoing process and will be undertaken by the SIMRAC Project on site response to rockbursts (GAP201).

11.2.6 Areal support in stopes

Testing of various different methods for a bolting and strapping system showed that this system gives good support and thus is not restricted to the VCR mines only. A new site for underground trials is being sought and the use of a non-VCR stope where the installation of bolts is already standard practice is recommended. Continued development of this system, including underground trials, is desirable.

11.3 Areas which are unlikely to be viable

No areas were identified that are unlikely to be viable.

11.4 Areas which should be discontinued

No work has continued to the end of 1996 that should be terminated as the remaining areas of study all show promise. However, little valuable information was obtained from extensometer results in view of unbedded lava hangingwalls. The requirement for this type of instrumentation should be reviewed in future monitoring programmes.