

# **Safety in Mines Research Advisory Committee**

**Final Project Report**

## **GAP 524**

# **A Study of Rockburst Source Mechanism**

**WD Ortlepp**

**Research Agency : Steffen, Robertson and Kirsten**  
**Project Number : GAP 524**  
**Date : June 2000**



# Table of Contents

## Summary and conclusions

	Page
<b>1 Introduction .....</b>	<b>1</b>
1.1 Main areas of uncertainty: .....	1
1.2 Damage effects:.....	2
1.3 Source characteristics:.....	2
<b>2 Review of prior knowledge .....</b>	<b>3</b>
<b>3 Research strategy and method .....</b>	<b>5</b>
<b>4 Location of rockburst ruptures .....</b>	<b>7</b>
<b>5 Description of main ruptures.....</b>	<b>9</b>
5.1 Visual appearance of ruptures .....	9
5.2 Microscopic studies:.....	11
<b>6 Mineralogy and chemistry of gouge material.....</b>	<b>13</b>
6.1 XRD analyses.....	14
6.2 XRF analyses .....	15
<b>7 Discussion .....</b>	<b>17</b>
7.1 Introductory thoughts .....	17
7.2 The origin of the rupture zone (source mechanism) .....	19
<b>8. References</b>	
Appendix 1. Features of 1974 ERPM study	
Appendix 2. Description of search target	
Appendix 3. Proposal	

# GAP 524

## Summary and Conclusions

The research project comprising GAP 524 involved detailed examination of a group of 3 rockburst ruptures or burst-fractures discovered in a VCR stope panel on a peninsular remnant on Mponeng Mine at a depth of 2550m below surface.

A careful visual study of the exposures was made, samples were taken and mineralogical and geochemical analyses conducted on the fractured rock and the finely comminuted fault gouge.

The most important conclusions were:

- In every important detail the 87-50 6<sup>E</sup> ruptures were effectively identical to the type example studied in 1974 on ERPM Ltd.
- This confirms that the shear rupture type of origin is an important sub-class of rockburst source mechanism.
- This type of rockburst is probably more common than previously believed and does not require any unfavourable geological structure or 'bad ground' as a necessary pre-condition for its occurrence.
- The relative direction of shear movement can easily be determined even without a stratigraphical marker and the sense of the movement is normal, dip-slip.
- There are strong indications that the rupture has its origin at some considerable distance from the reef plane. The fracture front is driven through pristine rock at high velocity, towards the stope abutment.

- Although there are intense frictional effects and probably quite high temperatures on the sheared surface; no chemical or mineralogical changes occur.
- In particular no coesite was found in the finely comminuted rock flour
- Considerable similarity exists between the mechanics of the rupture process and that involved in crustal earthquakes.
- As a result of this study a better foundation of understanding of rockburst source mechanism now exists on which to build future conjecture regarding important practical matters such as the magnitude of ground motion parameters like free-surface particle velocity and amplitude.

# 1 INTRODUCTION

After some 45 years of formal research into the rockburst problem, understanding of the **source mechanisms** of rockbursts is far from adequate. The major gaps in knowledge were outlined in the proposal motivation – Appendix 3. More importantly from a practical point of view, the lack of any proper understanding of the **mechanism of damage** prevents us from specifying accurately the strong ground motion parameters that the tunnel and stope support must be able to withstand and control. Knowledge of the source mechanism is a necessary pre-requisite for developing understanding of the mechanism of damage.

A consideration of the directions of more recent research will show that most effort has gone into seismological studies, numerical-modelling analyses of layout strategies with some laboratory-based fracture studies and post-facto examination of scenes of rockburst damage. Apart from a cursory examination of re-juvenated movement on major faults by van Aswegen (1990) no work has been done on the direct study of a rockburst source.

The belief underlying the GAP 524 proposal was that direct and detailed observation of the **source** of a damaging seismic event would lead to useful understanding of the physics of the rupture process. The scope of the research carried out in this GAP 524 project is restricted to that type of the double-couple or shear-displacement class of major seismic events which involves the fresh development of an extensive shear rupture through a previously intact rock mass. The hope and expectation was that this understanding would lead to improved ability to make reliable estimates of the damaging ground motion parameters.

## 1.1 Main areas of uncertainty:

The extent of the present lack of knowledge which it is hoped might be reduced by direct study of the rockburst source, is outlined below.

## 1.2 Damage effects:

The damage resulting from major rockbursts is often puzzling in the way that its extent and intensity cannot be explained simply on the basis of those seismological parameters which are normally most confidently revealed by the seismological network viz. the magnitude of the event and the location of its origin. The main characteristics of damage are that it is sometimes:

- very intense
- very localized
- indicative of very strong ground motion at the excavation surface, particularly peak particle velocity (PPV), that cannot be explained by simple seismological theory
- strongly directional or non-symmetrical, particularly in tunnels

Sometimes a ready explanation for localized damage is provided by the local geology, usually the presence of a fault or dyke, but frequently no reason is apparent.

## 1.3 Source characteristics:

Much of what is believed to be understood about the mechanism of the source of rockbursts has been borrowed from earthquake theory. While it is widely accepted that a broad identity exists between the two phenomena e.g. McGarr (1979) Segal and Pollard (1980) Sibson (1985), it is important to realize that much of the basis for earthquake understanding is necessarily very simplified and conjectural. This is unavoidably so because of the difficulty of verifying theory by direct examination of the actual surface of movement. Thus any additional knowledge gained from direct observation of the surfaces of a fault, which has incurred seismic slip, would be of benefit to both disciplines. In particular the following aspects most need clarification:

- Is the assumption of an approximately circular area of slip (as postulated in the Brune model) appropriate for the simple case of a single burst rupture or for movement on a single fault surface?

- How uniform is the amount of dislocation across the shear surface?
- If significantly non-uniform, are there identifiable features such as 'jogs' or asperities on the fault/rupture surface that could cause high stress drop. Rockbursts have been observed to incur stress drop two orders of magnitude higher than crustal earthquakes. Such 'impact asperities' could cause pulses of much stronger ground motion that might account for localized intense damage.
- Is rupture dislocation continuous along the source area, or can patches remain locked to form asperities that can become re-activated at a later stage?
- Does the shear rupture through geologically uncomplicated rock require a prepared path such as a concentrated alignment of pre-existing microscopic extension fractures, before it can propagate the dislocation?
- Is the direction of slip constant along the rupture surface and is it consistent with expectation based on theoretical stress distribution?

There is no doubt that many other aspects of the problem could be identified. It is also self-evident that pointers or clues to only some of these questions might emerge, mainly for those where a detailed direct examination of the actual sheared surfaces might reveal new insights.

## **2 Review of prior knowledge**

There is a vast amount of literature available concerning the mechanics of fracture in the earth's crust which aims to gain understanding of the earthquake process and which might therefore have some relevance to the study of rockburst mechanisms. The reference list in Sammis et al (1986) provides an indication of the development of this body of information.



The studies which have closer links with the rockburst problem and which in many cases actually make use of observations from South African gold mines include those of McGarr et al (1979), Olgaard and Brace (1983) Segal and Pollard (1980) Sibson (1985) (1986).

The observations used came almost exclusively from an extensive study of a rockburst rupture on ERPM Ltd from 1974 to 1975. This work is best described in papers by Gay and Ortlepp (1979), Ortlepp (1992) and Ortlepp (1997).

The study essentially involved exploration of the nature and extent of two fresh shear ruptures traversing through the rock mass, by developing a total of 90m of boxholes and small raises along the fracture traces. These 'burst fractures' had occurred ahead of the faces of a longwall which was stopping out an inclined shaft pillar in an unusually uncomplicated geological setting at a depth of 2050m below surface.

The 'follow-behind' footwall drive from which the raising was commenced revealed at least 20 traces of fractures of similar appearance and attitude along the 350m strike length of the shaft pillar. Although there was no seismic location network in the area it was possible by interpretation of the records from the WSSN station at Pretoria to associate the two explored fractures with damaging rockbursts that had occurred in September 1970.

The overall structure of the two fractures was established by careful surveying and geological mapping – Figure 1.1 in Appendix 1. The macro appearance was captured by more than 250 photographs. Samples of the fault gauge and adjoining wall rock enabled the micro-structure to be studied by thin-section microscopy and scanning electron microscopy (SEM). One of the SEM photographs showed features of extraordinary symmetry on which certain conclusions and conjectures have been based – Figure 1.2 in Appendix 1. Other photographs showing the visual identifying characteristics of rockburst ruptures are also grouped in Appendix 2 – Description of search target.

A tunnel has been driven on the Kamaishi Mine in north-eastern Japan, through the creeping section of an active fault zone known as the Mozumi fault. As far as is known the purpose is to enable creep measuring and other seismic instrumentation to be installed rather than to purposefully study the textures and substructures of its movement history or earthquake genesis. Very little has been published as yet.

Apart from the above cases it would appear that there are no other instances where attempts have been made to study the mechanism or genesis of major seismic activity by actual site examinations.

### **3 Research strategy and method**

For several reasons a shear rupture driven through intact rock may be expected to be the simplest form of a shear-type rockburst source. This is true at least in respect of its likely shape and extent even though the seismic signature may be complicated and its interpretation difficult or impossible. Re-juvenated movement on geological faults is probably the more frequent source mechanism for major seismicity but such features are very seldom freshly exposed by routine stoping or development shortly after the movement has occurred.

It was therefore decided at the outset to restrict the search for suitable shear fractures to those rockburst ruptures associated with stoping. Explanatory letters were written to the managers of 13 mines and additional notes and photographs illustrating the type of feature sought were sent to the respective rock engineering departmental heads – Appendix 2.

After 3½ months when no response had been elicited, presentations were held at venues in the Klerksdorp and Carltonville areas.

Exploratory visits were made to 94 level Tau Tona Mine and to 33/15 gulleys 6<sup>w</sup> and 7<sup>w</sup> of Deelkraal GM. Co Ltd. Samples of gouge material were taken from minor shear fractures which showed some of the main diagnostic characteristics of major rockburst ruptures. However none of these were convincing examples.

On 18 September 1998, as a result of 'feed-back' following the earlier presentation, a significant suite of three burst ruptures was identified at 87/50E 6 panel on Western Deep Levels South mine, now known as Mponeng. Visits to photograph, study and sample these features were made on several occasions. The study of these samples constitutes the main part of project GAP 524 and their description and the reporting of the results of the analyses form the bulk of this report.

To some extent the thrust of the research was determined by the exploration of the two major ruptures that was undertaken in 1974 on ERPM. This early study is probably the only deliberate exercise ever undertaken anywhere to explore the source region of a significant seismic event and it remains unique in respect of the extent of exposure of the shear surfaces and the number of detailed descriptive photographs taken of its morphology, textures and displacements. Seen in retrospect now, it is a matter for regret that no diagnostic work was done on the geochemistry of the comminuted gouge material and too little electron microscopy was undertaken. It nevertheless remains the definitive study of the source of a seismic event. The present study is, in effect, a confirmation and an extension of this earlier research effort.

A necessary part of the extension was the involvement of scientists able to provide the profound insights into the fundamental physics, geochemistry and micro-structural aspects that were lacking in the earlier work.

Dr Uwe Reimold of University of Witwatersrand appeared to be eminently suitable to direct the petrographical and geochemical aspects because of his specialized knowledge of impact structures in Witwatersrand rocks arising from his interest in the Vredefort structure and his overall depth of understanding of petrological and geochemical research.

The analyses were carried out at the Department of Geology by Richard Stewart, an honours student working under the guidance of Dr Reimold.

The types of analyses carried out, included the following:

- petrographic studies – optical microscope and SEM imaging of the rock material and the fracture distribution
- Mineralogic studies – X-ray diffraction (XRD)  
– X-ray fluorescence (XRF)
- SEM studies of fault gouge

The XRD analyses were particularly directed towards establishing whether it was possible that the very intense pressure and temperature changes on the shear surface might have resulted in a phase transformation of the quartz into coesite. Had this occurred, highly specialized fundamental physics insights would have been available in the person of Professor Didier Sornette of Nice University and University of California Los Angeles.

The results of the XRD showed that there was no trace of coesite present in the samples.

## **4 Location of rockburst ruptures**

The 87-50 E6 panel where the burst ruptures were exposed is shown in Figure 4.1 as it appeared at the time of their discovery on 10 September 1998.

The panel face was 40m long mining north-eastward on Ventersdorp Contact Reef towards the abandoned opposite face of the tip of a peninsular remnant about 30m wide. Close to the remnant tip was a 20m wide stabilizing pillar ‘buttressing’ the Trough dyke/fault which was about 100m away at its closest point – see Figure 4.2. The mined-out span between the Trough and the western flank of the ‘peninsula’ was about 100m for a considerable distance. Thus the remnant was shielded to some extent from the higher stress concentration that it might otherwise have been exposed to as a result of several hundreds of metres of stoped out area to the north-east, east and south-east. The depth of the remnant tip was 2555m below surface.

The Trough structure has been associated with enhanced seismicity and periodic large seismic events since first encountered on WDL East Mine decades before and some thousands of metres away. Figure 4.2 shows the locations of 30 events greater than  $M_L = 1.5$  which had occurred in the previous 19 months and been captured by the seismic network on the mine.

Of these located events, the two numbered 20 and 30 on Figure 4.2 were considered to be the most likely to have been associated with the rupture surfaces that were studied. Their elevations were about 18m below and 16m above the reef plane respectively, and their magnitudes were  $M_L = 1.7$  and 1.6.

The apparent stress and the energy index (parameters which are believed to be related to the suddenness or 'violence' of the slip movement) were 90 kPa and 1.3 for event 20 and 800 kPa and 12.1 for event 30. The latter two values would suggest that event 30 was the more likely to have been the responsible event. The inferred radius of 33m for the theoretical slip surface also seems to fit better to the subsequent observations than the 105m inferred for event 20.

The ruptures were first discovered by L. de Klerk of the Rock Engineering department when he was asked by the section shift-boss to determine the reasons for unusually 'bad ground' conditions encountered by the miner. No mention was made of rockbursts having caused damage in the stope. The 'bad ground' had been encountered as the panel face had advanced into it. Difficulties of maintaining the stope width and supporting the bad hanging wall at the face then proved to be virtually insurmountable. The miner then left the upper half of the panel and advanced only the lower half intending to 'open - raise' up-dip through the bad ground.

This advance revealed steeply eastward dipping burst fractures 2 and 3 the footwall traces of which are shown in Figure 4.3. The upward extension of rupture 2 had resulted in some shattering of the lava hangingwall and it was this shattering that caused the 'bad ground'. Rupture 1 was revealed in the west wall of a dip-gulley that had been established close behind the face.

It was decided that the safest way of extracting the remnant was by advancing a strike face in a down-dip direction. This decision was fortunate since it enabled several visits to be made to the main exposure and additional observations to be carried out in the centre of the remnant. Figure 4.3 shows the position of the down-dip face at two monthly intervals there after.

Three to four dip-aligned, steeply eastward - dipping fractures with small dip-slip displacements and minor comminution were observed and photographed on each occasion. None of these features was nearly as well-defined or dramatic as rupture traces 1, 2 or 3. The most distinct is indicated as photo [5] on the visit of 25.11.98 on Figure 4.3. This photograph is reproduced as Photograph 4.1 in the body of this report.

In addition to Prof. Uwe Reimold of Witwatersrand University, other eminent academics who were able to see the features included Prof. Tom Jordan of Massachusetts Institute of Technology and Prof. Larry Myer of University of California, Berkeley. Importantly, the fractures were also examined by Dr. John Napier of CSIR Miningtek and Dr G van Aswegen of ISSI.

## **5 Description of main ruptures**

The three main rupture surfaces each showed clearly the features which are quite peculiar to rockburst ruptures or 'burst fractures'. These definitive characteristics are:

- very finely comminuted 'rock flour' on an obviously freshly-sheared surface.
- a relatively extensive, near perfectly planar surface showing a strongly textured lineated appearance like a greatly enlarged, sharp-edged metal-working single-cut file. This has been described as a 'hackled' surface in the earlier work and is probably the most definitively diagnostic feature of a burst rupture.
- a shear displacement or off-set of several centimetres in a dip-slip, normal sense.
- 'pinnate joints' or subsidiary extension fractures extending away from the surface of shear movement for several millimetres to several centimeters.
- the acute angle between these secondary extension features and the main shear surface always points in the direction of relative motion of the shear movement.

### **5.1 Visual appearance of ruptures**

The macro appearance of the diagnostic features listed above is best conveyed by the photographs as follows:

Photograph 5.1.1: viewed westward across the dip gully, rupture 1 exposed the typical strong lineation of the 'hackle' surface over the full depth of the gully sidewall for a distance of several metres. The direction of the lineation is parallel to the dip of the stope footwall indicating that the slip direction is perpendicular to the reef dip. Figure 5.1.1(a) is a composite

diagrammatic section which shows the relative locations of ruptures 1, 2 and 3.

Photograph 5.1.2: a view north-westward of rupture 2 shows the hackle surface exposed on two fault-scarps each of about 200mm high.

Photograph 5.1.3: a closer view of the 'fault scarp' of rupture 2 shows that the two hackle surfaces are actually two segments of the same shear surface which has 'jogged' to the left as indicated in the diagrammatic sketch of Figure 5.1.3 (a). The displaced shear surface is interconnected across the off-set or 'jog' by several cross-linking, parallel subsidiary shears in identical fashion to that shown in Photograph 2.1(a) and 2.1(b) of Appendix 2. Sibson (1985) identified similar features on segments of the San Andreas fault, explaining left-stepping jogs on right lateral movement faults as 'anti-dilational' (compressional) features.

Photograph 5.1.4: view northward of rupture 3 as it disappears into the top corner of the lower half of E6 panel. A darker sedimentary marker shows clearly a normal dip-slip sense of movement with almost 100mm of displacement.

Photograph 5.1.5: a similar view to the above with more oblique lighting emphasizing the jagged edge of the shear surface and the texture of the hackle surface extending to the right down the face. The longer pinnate joints cut the footwall block of the 'fault' into a set of trapezoidal blocks which made it easy to take good samples of the hackle surface and associated smaller subsidiary features.

Photograph 5.1.6: provides a close view of the lineated texture of the hackle surface which extended for some few metres along the stope face.

Photograph 5.1.7: gives a very close view of an intensely sheared fragment trapped on the shear surface.

Photograph 5.1.8: is a close-up of a polished slice cut through one of the trapezoidal prisms. Slices such as this allowed a very close macro and micro study of the nature of the hackle surface and the smallest subsidiary fractures.

Photograph 5.1.8 (a) shows ultra close-up detail of the smallest 'feather' fractures.

Note that these only extend downwards, never upwards, from the 'spine' of the short pinnate joints.

## 5.2 Microscopic studies:

It is generally accepted that the essential fracture process in brittle rock is one where pure tensile failure commences initially at the tip of an elemental crack or flaw (a 'Griffith crack') and further breakdown proceeds as an *extension* or indirect tensile fracture growing in the direction of the maximum principal stress.

In classic experimental studies by Hallbauer et al (1973) it was demonstrated that failure of a cylindrical specimen of quartzite takes place through the formation of many small extension fractures pervasively through the stressed volume. Final fracturing takes place along shear surfaces where the extension fractures become localized and most concentrated.

As the occurrence of a rockburst rupture is an expression of final unstable failure, it might be supposed that a necessary pre-condition would be the existence of a pattern of aligned micro fractures with marked localization and concentration along the shear surface. The shearing movement would only occur when failure took place suddenly along the prepared surfaces.

It is considered that one of the more important conclusions arising from the GAP 524 research is that such pre-conditioning of the rock fabric does not happen. This was clearly demonstrated by all of the optical microscopic studies carried out on the thin sections made from the close vicinity of the rupture.



Photograph 5.2.1 shows the edge of the 'solid' rock alongside the intensely comminuted sheared surface and three inclined small 'pinnate micro-joints' extending away from it. Photograph 5.2.2 is an enlarged view of one of these subsidiary cracks.

The three 'pinnate micro-joints' of Photograph 5.2.1 are clearly the same cracks as those evident as the 5-10 mm 'spines' of the 'feather fractures' in the polished section of Photograph 5.1.8. Careful examination of the upper two of these micro-joints show that two or three branches have developed which extend downward toward the next micro-joint below but appear not to reach it. There is a strong suggestion that only downward pointing branches develop. This tendency is evident also in the polished sections – see Photograph 5.1.8 (a) – where sub-feathers form only on the downward side.

There can be little doubt that the mechanism for the creation of the micro-cracks is that strong tensile forces develop on the shearing surface probably where opposing high points or asperities over-ride one another. These tensile forces tend to tear or pluck the protrusion away from its substrate. The final downward-pointing branch or 'sub-feather' is also a tensile fracture suggestive of a slight rotational tendency of 'cantilevered' micro-plates.

The importance of these observations and the above explanation is that they preclude the existence of, or the need for; a pre-existing fabric of localized and concentrated micro-fractures that softens or pre-conditions the stressed rock to provide a path for the eventual shear rupture.

The alternative explanation which is confidently proposed here is that the shear rupture originated at some origin remote from the stope and explosively propagated through an unfractured rock mass towards the stope. The comminuted rock flour and hackly surfaces develop as a result of the intense frictional effects on the walls of shear rupture as they move into their preferred more relaxed positions. The pinnate joints and micro-joints or feather fractures are all secondary effects.

The most telling evidence of the non-existence of a preconditioned 'path' is simply the lack of any signs of micro fractures except within the immediate vicinity of the sheared surface or within a few grain dimensions of the subsidiary fractures e.g. Photograph 5.2.2.

Exactly similar evidence was yielded by the ERPM studies e.g. page 56 of Ortlepp (1997).

One of the more interesting indications of the violence of the micro-fracturing processes afforded by that study on p.57, was the existence of sub-microscopic rhombic dodecahedral particles – Photograph 1.2 in Appendix 1. Although no identical features were discovered in the SEM photographs of the GAP 524 study, a similar indication that ‘shattering’ of grains occurred along the rupture edge, can be seen in the thin section of Photograph 5.2.3 and in the SEM Photograph 5.2.4.

The micrographs referred to in the preceding section were selected primarily to show the absence of intra granular fracturing at distances greater than a few grain diameters from the main shear surface or the subsidiary fractures and the presence of ‘shattering’ close to the shear.

Many more excellent micrographs are to be found in the dissertation by R.A. Stewart (2000) which together with his detailed interpretation provide a comprehensive description of the complete cataclasis process.

## **6 Mineralogy and chemistry of gouge material**

There were two main reasons for conducting mineralogical and chemical analyses of the rock material in the ruptures.

Apart from a rather superficial search for signs of fused material, the previous study of the ERPM burst fractures did not consider mineralogical or chemical changes at all. GAP 524 thus provided an opportunity to search for differences in mineralogy and chemistry in the surrounding quartzite, the quartzite affected by shearing and the fault gouge material.

The minute polyhedral particles of Photograph 1.2 of Appendix 1 which were explained by Ortlepp (1997) as an **isotropic tensile shock** effect, have more frequently been interpreted by others as minute crystals. In one specific interpretation they were identified as squat basal prisms of coesite. Coesite is a high temperature, high pressure polymorph of silica which is found in nature only at meteorite impact craters and other sites of very

intense dynamic metamorphism. If coesite had been found it would have had far-reaching implications in the study of earthquake origins.

The techniques used in the analyses were X-ray diffraction (XRD) and X-ray fluorescence (XRF).

## **6.1 XRD analyses**

The quartzite comprises dominantly quartz and illite. The results of the qualitative analysis are displayed in Table 6.1.1.

In most of the samples a subtle muscovite signature could also be seen. There was no difference between the unsheared and the sheared quartzite. The fault gouge generally appeared to show a very subtle difference in that the muscovite signature was very weak and in some of the samples totally absent.

In a special examination, portions of samples of gouge and the most intensely brittle deformed material were finely milled and subjected to hydrofluoric acid treatment in order to dissolve quartz and lower its concentration relative to any proportion of other silica polymorphs (such as coesite). Some ten sample portions were repeatedly treated and re-analysed but no trace of any high-pressure minerals could be detected.

**Table 6.1.1**  
**XRD results**

<b>Sample</b>	<b>Description</b>	<b>Mineral present</b>
WD 1	Solid, unsheared quartzite	Quartz + Illite + (muscovite)
WD 2	Sheared quartzite (Central shear zone)	Quartz + Illite + (muscovite)
WD 3	Sheared quartzite (central shear zone)	Quartz + Illite + (muscovite)
WD 4	Sheared quartzite (central shear zone)	Quartz + Illite + (muscovite)
WD 5	Sheared quartzite (central shear zone)	Quartz + Illite
WD 5a	Fault gouge (Eastern Shear Zone)	Quartz + Illite
WD 5b	Fault gouge (Eastern Shear Zone)	Quartz + Illite + (muscovite)
WD 6	Sheared quartzite (Eastern shear zone)	Quartz + Illite + (muscovite)
WD 7	Sheared quartzite (Eastern shear zone)	Quartz + Illite + (muscovite)
WD 8	Sheared quartzite (Eastern shear zone)	Quartz + Illite + (muscovite)
WD 10	Fault gouge (Central shear zone)	Quartz + Illite + (muscovite)
WD LB	Fault gouge (Central shear zone)	Quartz + Illite
DO 1	Sheared quartzite (Eastern shear zone)	Quartz + Illite + (muscovite)
DO 2	Sheared quartzite (Eastern shear zone)	Quartz + Illite + (muscovite)
DO 11	Sheared quartzite (Eastern shear zone)	Quartz + Illite + (muscovite)
DO 21	Hartebeesfontein mine – jointed quartzite	Quartz + Illite + muscovite + pyrophyllite
DO 22	Hartebeesfontein mine – jointed quartzite	Quartz + pyrophyllite
DO 23	Hartebeesfontein mine – jointed quartzite	Quartz + Illite muscovite + pyrophyllite

## 6.2 XRF analyses

Three samples of fault gouge, seven samples of sheared quartzite and one sample of unsheared quartzite were subjected to XRF analysis. The results obtained are given in Table 6.2.1.

The results were also plotted in the form of ternary diagrams – Figure 6.2.1. Two of the diagrams represent the most dominant of the major elements, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and K<sub>2</sub>O while

the remaining two represent the less dominant, major elements, namely Fe<sub>2</sub>O<sub>3</sub>, CaO and Na<sub>2</sub>O<sub>3</sub>.

Figure 6.2.1 and 6.2.2, show similar results, namely that there is a definite similarity between the chemistry of the fault gouge and the sheared and unsheared quartzite. All of the above mentioned materials show similar positions on the ternary diagrams, with no apparent grouping between the different rock types i.e. fault gouge, sheared and unsheared quartzite. The unsheared quartzite plots roughly in the centre of all of the samples. It thus appears that the rocks have not undergone any obvious change in chemistry during the shearing of the rock, irrespective of the degree of deformation that the rock has experienced. Figure 6.2.3 and 6.2.4 show similar results. Although in this ternary diagram, the spread of the data is slightly larger than in the first two diagrams, again there does not appear to be any apparent grouping between different rock types. The two ternary diagrams thus support the fact that the changes of the rocks during the deformation event, are clearly isochemical changes when observing the chemistry on the broader scale. For a more complete discussion of the chemical and mineralogical analyses and interpretations, refer to Stewart (2000).

**Table 6.2.1**  
**XRF results**

	Material	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>
WD 1	UQ	77.66	0.27	14.94	0.57	0	0	0.15	0.24	4.41	0.01
WD 2	SQ	78.06	0.27	14.65	0.53	0	0.07	0.16	0.24	4.26	0.01
WD 3	SQ	79.56	0.24	13.69	0.76	0	0	0.13	0	4	0.02
WD 4	SQ	74.62	0.29	16.94	0.64	0	0.05	0.16	0.29	4.97	0.01
WD 5	FG	79.09	0.28	14.16	0.56	0.01	0	0.19	0.26	4.1	0
WD 5b	FG	89.99	0.27	14.08	0.57	0.01	0	0.18	0.27	4.09	0.02
WD 6	SQ	92.78	0.13	8.71	0.87	0	0	0.06	0.01	1.59	0.01
WD 8	SQ	93.11	0.12	4.63	1.04	0.01	0.12	0.08	0.06	1.23	0.01
WD 10	FG	93.11	0.1	5.15	0.94	0.01	0	0.04	0.03	1.44	0.01
WDLB	FG	84.79	0.27	10.06	0.39	0.01	0	0.16	0.19	2.94	0.02
DO 1	SQ	80.84	0.18	13.07	0.49	0	0	0.09	0.24	3.9	0.02
DO 2	SQ	78	0.21	14.28	0.81	0.01	0.5	0.19	0.19	4.18	0.02

**Table 6.2.1 (continued)**

	<b>Material</b>	<b>RB</b>	<b>Sr</b>	<b>Y</b>	<b>Zr</b>	<b>Nb</b>	<b>Co</b>	<b>Ni</b>	<b>Cu</b>	<b>Zn</b>	<b>V</b>	<b>Cr</b>	<b>Ba</b>
WD 1	UQ	167	37	12	87	9	10	36	2	9	40	144	1144
WD 2	SQ	171	38	12	89	9	9	32	2	11	38	147	1157
WD 3	SQ	160	37	10	75	8	11	35	2	10	39	124	1042
WD 4	SQ	196	44	18	106	8	9	35	2	10	46	146	1267
WD 5	FG	164	37	12	96	8	12	34	2	9	42	148	1150
WD 5b	FG	159	40	11	89	9	9	28	2	15	43	158	1099
WD 6	SQ	47	13	6	65	7	8	21	8	142	23	65	363
WD 8	SQ	64	17	6	65	7	9	41	6	29	28	77	523
WD 10	FG	62	17	4	45	7	10	26	2	77	24	51	473
WDLB	FG	117	29	11	94	9	11	37	2	10	32	149	858
DO1	SQ	155	34	10	64	7	8	24	2	10	33	84	1162
D02	SQ	133	31	8	51	8	7	26	2	10	34	104	1034

Materials: UQ = unsheared Quartzite  
SQ = Sheared Quartzite  
FG = Fault Gouge

## **7 Discussion**

### **7.1 Introductory thoughts**

It is not easy to evaluate the useful contribution to knowledge that might derive from the results of the research carried out under GAP 524. In the form of directly applicable, quantitative, practical design information it is likely that little of significance has been achieved. On the other hand it can be argued that a solid foundation of real factual observation has been provided on which hypotheses of the fundamental mechanism of rockburst origin can be built, where none existed before.

To help evaluation, it may be useful to consider the present status in earthquake research:

“...A better understanding of the physics of the earthquake process should enable the development of seismic hazard assessment tools. This development would be based on improved estimates of the locations and sizes of future earthquakes and the time dependent probabilities of their occurrence. It will also allow incorporation of realistic simulations of dynamic rupture and wave propagation into hazard models so that the time histories of strong ground shaking (from scenario earthquakes) necessary for performance-based seismic design of structures can be synthesized”

“...while a unified framework for earthquake physics does not exist, a good common reference may be the equations of motion for a continuum solid...”

The above thoughts formed the preamble by Yehuda Ben-Zion to a workshop of the Southern California Earthquake Centre in Idaho in June 1998.

A moments reflection on these notions will show that they are essentially the same as the objectives which (perhaps not yet properly articulated) should be seen to be driving our ultimate search for solutions to the rockburst problem.

1. we need to develop reliable seismic hazard assessments as the criteria for comparing different possible mining layouts and for implementing ‘warning’ or ‘labour withdrawal’ procedures in hazardous areas.
2. we need reliable estimates of **strong ground shaking** parameters (peak ground velocity and duration) to enable proper engineering design of tunnel and stope support characteristics.

As in most of the entire realm of physics, direct observations that can be measured or otherwise simply quantified, form the cornerstones of understanding. In earthquake physics the source process cannot be observed directly.

In the case of seismicity associated with underground mining, the source region **can** sometimes be discovered and explored. The possibility of directly observing the imprint of the source processes of an actual seismic event therefore provides an invaluable and

unique opportunity to improve understanding of both earthquake and rockburst source mechanisms.

## **7.2 The origin of the rupture zone (source mechanism)**

It has been suggested by many earthquake researchers e.g. Sammis et al (1986), Sibson (1985) (1986), Segal and Pollard (1980) that the fracturing processes involved in crustal fault zones are likely to be largely scale-invariant. Certainly it has been widely accepted that the mechanisms involved are sufficiently self-similar to justify the extrapolation of laboratory studies on brittle rock materials into the field of crustal faulting.

The results of GAP 524 do not, in any way, seek to refute or contradict such concepts. On the contrary the hope is that it provides additional evidence on a scale intermediate between crustal faults (on a scale of tens of kilometers) and laboratory fractures (on a scale of millimeters), to support these ideas. It is suggested that observations of fractures ranging from meters to tens of meters in length which extend through the rock mass surrounding mine excavations of large area, provide an opportunity to speculate upon the genesis of the complete fracture event.

Two extreme postulates may be offered:

On the one hand the 'mine fault' or rockburst rupture might be visualized as an evolutionary process which commences with the localisation and alignment of very small extension fractures (on a scale of a few tens of millimetres). These, in due course, are suddenly linked up into ... "one or more relatively planar and discrete through-going principal slip surfaces ...". Sibson (1986) sees the principal slip surface as the progressive development of an 'initiating infrastructure' of pre-existing subsidiary shears. The rapid linking together of the pre-existing surfaces often gives rise to seismic events with moment magnitude between  $M_L = 1,0$  and  $M_L = 3,0$ . The shear zones of GAP 524 were probably associated with events of  $M_L = 1,8$  or  $1,6$ .

The alternative postulate proposes that the shear rupture spreads as a very rapidly extending fracture front through a pristine highly - stressed (but not yet failed) rock space.



It initiates at an existing flaw which initially grows in a stable fashion to some critical size. Increasing stress causes it to 'erupt' along a path which is initially determined by the orientation of the deviatoric stress vector. The critical, unstable value of stress results from the superposition of the continually changing mining-induced stress upon the original residual geologic stress field. All the subsidiary tensional or extensional minor fractures such as 'pinnate' joints or the small cross-linking shears are secondary features. These would be caused by the intense frictional effects along the shearing surface in the case of the extensional features and by interaction between the stress concentrations at the overlapping ends of fault segments in the case of the small cross-linking shears.

The main points of evidence which could be adduced in favour of the evolutionary genesis hypothesis would be:

1. the detail of the inter-relationship between the microscopic and sub-microscopic 'explosion' breccias and the macro structure of the intensely sheared surfaces.
2. The continuous background of low-level seismic activity which may be indicative of the micro-fracturing which prepares the narrow zones of subsidiary shears and extension fractures along which the main shear surface will progress.

The main features of previously observed shear rupture surfaces (e.g. Ortlepp 1992) which reject the above evolutionary hypothesis, are:

1. the remarkable planarity and continuity of the ruptures on the large scale of tens of meters
2. the complete lack of damage, even on a submicroscopic scale, in the rock fabric within centimeters of the main shear surfaces and within millimeters of the subsidiary fractures such as the pinnate joints.

When visualised from a perspective which embraces the entire burst rupture extending over a few thousand square meters in area, it seems improbable that the pre-conditioning process could be confined to such an extraordinarily narrow zone only millimetres or centimeters wide. This is particularly so when the rock mass is relatively homogeneous and the ambient stress field is believed to vary relatively smoothly.

From a practical point of view it is important to determine whether the shear rupture originates at some distance from the stress-perturbing agent (the mine excavation) and erupts violently at near seismic velocity **towards** it through a pristine rock mass or whether it grows more or less steadily **away** from the excavation along a prepared path out into the surrounding rock space. The former picture would fit better with a real situation of rock bursts occurring occasionally and very sporadically but often with directionally-focussed violence. A kind of “Doppler shock effect” might help explain some of the evidence of very high particle velocities that have been observed (Ortlepp 1993).

## References

1. GAY, N.C. AND ORTLEPP, W.D. (1979) Anatomy of mining-induced fault zone. *Geological Society of America Bulletin*. 90: 47-58 Part 1
2. HALLBAUER, D.K., WAGNER, H. and COOK, N.G.W. (1973). Some observations concerning the microscopic and mechanical behaviour of quartzite specimens in stiff triaxial compression tests. *Int. Journal Rock Mechanics and Min. Science*. 10 pp 713-726.
3. MCGARR, A., POLLARD, D., GAY, N.C. AND ORTLEPP, W.D. (1979) Observations and analysis of structures in exhumed mine-induced faults. *U.S. Geological Survey Open File Report*. 79-1239 pp 101-120.
4. OLGAARD, D.L. and BRACE, W.F. (1983) The microstructure of gouge from a mining-induced seismic shear zone. *Int. J. Rock Mech and Min. Sci.* 1983 20 (I): 11-9
5. ORTLEPP, W.D. (1992), Note on fault-slip motion inferred from a study of micro-cataclastic particles from an underground shear rupture. *Pageoph* 139, No. 3/4, 677-695.
6. ORTLEPP, W.D (1993), High ground displacement velocities associated with rockburst damage. *Rockbursts and Seismicity in Mines 93. Proc. of 3<sup>rd</sup> Int. Symp.* Kingston, Ont. Aug 1993 pp 10
7. ORTLEPP, W.D. (1997) Rock fracture and Rockbursts – an illustrative study. Johannesburg. *SAIMM Monograph Series M9*.
8. SAMMIS, C.G., OSBORNE, R.H. ANDERSON, J.L., BANERDT, M., and WHITE, P. (1986) Self-similar cataclasis in the formation of fault gouge. *Pageoph*, 124 Nos. 1 / 2 54-77.

9. SEGALL, P. and POLLARD, D.D. (1980), Mechanics of discontinuous faulting. *Journal Geophys. Res.* 85, 4337-4350.
10. SIBSON, R.H. (1985), Stopping of earthquake ruptures at dilational fault jogs. *Nature* 316, 248-251
11. SIBSON, R.H. (1986), Brecciation process in fault zones: Inferences from earthquake rupturing. *Pageoph* 124, No. 1 / 2, 159-175.
12. STEWART, R.A. (2000), The nature and characteristics of fault gouge material associated with a shear zone related to a recent rockburst. Unpublished dissertation, Department of Geology, University of the Witwatersrand.
13. VAN ASWEGEN, G (1990) Fault stability in S.A. gold mines. *Proceedings of the Int. Conference on Mechanics of Jointed and Faulted Rock*. P. Rossmannith (ed.) Vienna, Austria, April 1990.

g:\proj\248297\gap5242000.doc/14/04/00

## Appendix 1

### **Features of 1974 ERPM study**

Figure 1.1                      Isometric view of the two main shear ruptures exposed on ERPM in 1974

Photograph 1.2:              SEM photograph of rhombic dodecahedral-shaped sub-particles from ERPM fault gouge

## **Appendix 2**

- List of mines contacted
- Letter of request to mine manager
- Letter to head of rock mechanics department
- Guidelines for burst-rupture/fault-slip search
- Photographs of typical features of burst fractures

**GAP 524: Source Mechanism Study**  
**List of mines contacted**

<b>Rock Mechanics</b>	<b>Mine</b>	<b>Address</b>
Mr Quintin Brown	ERPM	PO Box 2227, Boksburg, 1460
Mr Jannie de Lange	Elandsrand	Private Bag X2025, Carletonville, 2500
Mr Peter Jenkins	East Driefontein	Private Bag X2016, Goudveld, 2507
Mr A W Stillwell	West Driefontein	Private Bag X2011, Carletonville, 2500
Mr Johan Laas	Vaal Reefs	Private Bag X5010, Vaal Reefs, 2621
Mr Koos Bosman	Hartebeestfontein	Private Bag 800, Stilfontein, 2550
Mr Gary Williams	Buffelsfontein	Private Bag, Stilfontein, 2550
Mr Matthew Handley	Western Leels	P.O. Box 8044, Western Levels, 2501
Mr Nico van Rensburg	Western Areas	P.O. Box 190, Western Areas, 2580
Mr Kevin Wright	Blyvooruitzicht	P.O. Box 7001, Blyvooruitzicht, 2504
Mr Andrew Ozinski	President Steyn Mine	P.O. Box 2, Welkom, 9460

323232/ORTL/hugo

25 March 1998

Elandsrand  
Private Bag X2025  
Carltonville  
2500

Fax No. 018- 782 1132

**Attention: Mr Jannie de Lange,**

Dear Mr de Lange,

### **GAP 524: Source Mechanism Study**

**Supplement to the letter to the Mine Manager dated 25 March 1998, copy of which is enclosed.**

It is generally accepted that large to major seismic events are usually the result of shear displacements along existing faults but sometimes result from fresh ruptures driven along a roughly planar surface through massive >clean= ground.

There are important gaps in our knowledge, however, which make it difficult to derive practical benefit from this broad understanding. Among the more important shortcomings are:

- X insufficient evidence exists as to how much displacement actually occurred along the shear surface, and in what direction and with what velocity.
- X how are the very strong ground motions (that are sometimes so clearly indicated by the observed damage), actually generated?
- X why do very large events of similar magnitudes sometimes cause violent damage to adjacent excavations and sometimes surprisingly little?
- X is the variability in damage potential a function of the stiffness of the mine structure (seen as a regional system which is controlled by regional support)? Or is it perhaps intrinsic to a particular fault due to the character of its filling or gouge material or to its continuity or planeness etc? (If we had this knowledge and studied fault traces carefully at an early stage in the mines life, would we be able to avoid situations of particularly high hazard potential later on?).



In summary, there is so little known about how the seismic event **source mechanism** relates to the **damage mechanism** that it is really not possible to rationally develop an effective management strategy to deal with the problem of major rockbursts.

There still remains a real hope for mine operators and their design teams to discover some of these vital relationships because it is possible, in some deep mines, to locate, explore and measure what has actually happened in the rock mass where seismological monitoring has indicated that a large rockburst has occurred. (This possibility does not exist for civic authorities in urbanized earthquake areas, for example, whose design teams - backed by earthquake physicists - will never be able to directly explore the earthquake source).

It is the purpose of this SIMGAP 524 project to **locate major rockburst sources and examine their physical attributes, in order to understand the essential physics of the phenomenon**. Important traces of these processes must, to some extent at least, still form part of the fossil >imprint= left by the event.

By involving academics of the highest calibre from the USA and a local university who bring with them the disciplines of pure physics, applied geophysics, geology and high pressure mineralogy, the project will be able to apply the most advanced thinking and technologies to the understanding of the problem.

We hope that, by forming the >advance search party= you will be able to become part of the team.

Realizing that important exposures are often soon obscured by the mining process we would like to suggest that any promising features that might be discovered should be photographed and scanned into the E-mail system (if you have access to such facilities) and sent to my E-mail address as soon as possible after the discovery.

Samples of finely-comminuted >rock-flour= should be carefully prised out of the fracture, wrapped in tissue paper and carefully handled so that any self-adherent >lumps= do not break down into powder.

The hope is that access to the feature could then be maintained for long enough to enable further detailed study to be made by the local academic and myself or, in the most exciting cases, by the overseas person as well.

In order to facilitate the search (and avoid possible waste of time resulting from mis-identification) the enclosed descriptions of the >target= and >target area= are offered.

Might I suggest that, in order to increase the size of the >search party=, you make reproductions of these and give copies to all members of your department and other personnel such as stope observers and prop recorders who spend much of their working hours in stopes or follow-on-tunnels.

I look forward with great anticipation to hearing of your first discovery!

My E-mail address is :           pwilkins@srk.co.za

My telephone numbers are : 011- 441 1256 [work]  
  011- 706 3531 [home]

Yours sincerely,

**Dave Ortlepp**  
Steffen, Robertson and Kirsten

g:\proj\323232\another\ortl\heads.let

323232/ORTL/hugo

25 March 1998

Elandsrand  
Private Bag X2025  
Carltonville  
2500

Fax No. 018- 782 1132

**Attention: Mr Jannie de Lange,**

Dear Mr de Lange,

### **GAP 524: Source Mechanism Study**

**Supplement to the letter to the Mine Manager dated 25 March 1998, copy of which is enclosed.**

It is generally accepted that large to major seismic events are usually the result of shear displacements along existing faults but sometimes result from fresh ruptures driven along a roughly planar surface through massive >clean= ground.

There are important gaps in our knowledge, however, which make it difficult to derive practical benefit from this broad understanding. Among the more important shortcomings are:

- X insufficient evidence exists as to how much displacement actually occurred along the shear surface, and in what direction and with what velocity.
- X how are the very strong ground motions (that are sometimes so clearly indicated by the observed damage), actually generated?
- X why do very large events of similar magnitudes sometimes cause violent damage to adjacent excavations and sometimes surprisingly little?
- X is the variability in damage potential a function of the stiffness of the mine structure (seen as a regional system which is controlled by regional support)? Or is it perhaps intrinsic to a particular fault due to the character of its filling or gouge material or to its continuity or planeness etc? (If we had this knowledge and studied fault traces carefully at an early stage in the mines life, would we be able to avoid situations of particularly high hazard potential later on?).

In summary, there is so little known about how the seismic event **source mechanism** relates to the **damage mechanism** that it is really not possible to rationally develop an effective management strategy to deal with the problem of major rockbursts.

There still remains a real hope for mine operators and their design teams to discover some of these vital relationships because it is possible, in some deep mines, to locate, explore and measure what has actually happened in the rock mass where seismological monitoring has indicated that a large rockburst has occurred. (This possibility does not exist for civic authorities in urbanized earthquake areas, for example, whose design teams - backed by earthquake physicists - will never be able to directly explore the earthquake source).

It is the purpose of this SIMGAP 524 project to **locate major rockburst sources and examine their physical attributes, in order to understand the essential physics of the phenomenon**. Important traces of these processes must, to some extent at least, still form part of the fossil >imprint= left by the event.

By involving academics of the highest calibre from the USA and a local university who bring with them the disciplines of pure physics, applied geophysics, geology and high pressure mineralogy, the project will be able to apply the most advanced thinking and technologies to the understanding of the problem.

We hope that, by forming the >advance search party= you will be able to become part of the team.

Realizing that important exposures are often soon obscured by the mining process we would like to suggest that any promising features that might be discovered should be photographed and scanned into the E-mail system (if you have access to such facilities) and sent to my E-mail address as soon as possible after the discovery.

Samples of finely-comminuted >rock-flour= should be carefully prised out of the fracture, wrapped in tissue paper and carefully handled so that any self-adherent >lumps= do not break down into powder.

The hope is that access to the feature could then be maintained for long enough to enable further detailed study to be made by the local academic and myself or, in the most exciting cases, by the overseas person as well.

In order to facilitate the search (and avoid possible waste of time resulting from mis-identification) the enclosed descriptions of the >target= and >target area= are offered.

Might I suggest that, in order to increase the size of the >search party=, you make reproductions of these and give copies to all members of your department and other personnel such as stope observers and prop recorders who spend much of their working hours in stopes or follow-on-tunnels.

I look forward with great anticipation to hearing of your first discovery!

My E-mail address is :           pwilkins@srk.co.za

My telephone numbers are : 011- 441 1256 [work]  
  011- 706 3531 [home]

Yours sincerely,

**Dave Ortlepp**  
Steffen, Robertson and Kirsten

g:\proj\323232\another\ortl\heads.let

## **Guideline for burst-rupture/fault-slip search**

The following situation would indicate promising locations where one might expect to find a feature suitable for source mechanism studies.

### **Scattered mining**

- Main access tunnel through major fault after major seismic event – see photo enclosed.
- Stopping through a minor fault after a large rockburst which might have occurred some months previously when the stope face was 10 to 30 m from the fault.

### **Longwall Mining**

- As above when stopping through a minor fault.
- During up-dip operations to re-establish the breast face, after large burst caused a temporary loss of a panel.
- Continuation of normal stoping operations for the 10 to 30 m after a large rockburst occurred with a nearby source location.
- In a 'follow-on' hanging wall or footwall drive. (This would be a particularly favourable location because of the possibility of continued access for a considerable time after first exposure).



## **Appendix 3**

PROPOSAL





