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## Violent failure of a remnant in a deep South African gold mine

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### Abstract

The violent failure of a peninsular remnant at a depth of 2300 m below surface occurred in a mine in the Carletonville Goldfield of South Africa, severely damaging a stope mining the Ventersdorp Contact Reef (VCR). At the rockburst site the VCR is 1–2 m thick with a lava hangingwall and quartzite/conglomerate footwall. The remnant had been formed as the result of a fault and ‘roll’ encountered during mining. Observations at the rockburst site led us to conclude that the seismic event, with local magnitude of 2.1, resulted from failure of the remnant with attendant movement into the workings. The event could not be explained by a single shear slip. Two different damage mechanisms were identified. Firstly, the face and footwall on the east side of the remnant were violently ejected into the void between the original face and first line of timber packs following failure and dilation of the remnant and its foundation. Secondly, the hangingwall on the south side of the remnant fragmented and collapsed when subjected to intense seismic shaking. This response was due to the presence of a bedding-parallel fault and calcite-coated joints in the vicinity of a ‘roll’. The stope support system failed to contain the seismically fragmented rock. © 1998 Elsevier Science B.V. All rights reserved.

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### 1. Introduction

In 1994 the South African mining industry initiated a research project with the objective of determining the causes of damaging seismic events. It is believed that a detailed understanding of both the source and damage mechanisms, and the application of this knowledge to the mining and support of excavations will lead to a reduction in the hazard posed by rockbursts. Here we describe the second investigation conducted under the auspices of this project.

On 4 May 1994 a rockburst occurred in a mine in the Carletonville Goldfield of South Africa (Fig. 1). A stope mining the Ventersdorp Contact Reef (VCR) (Fig. 2) at a depth of 2300 m below surface was severely damaged (Fig. 3). The mine seismic network recorded a single seismic event at 09h49 with a local magnitude of 2.1. The mining layout afforded an unusual opportunity to investigate the source and damage mechanisms associated with the violent failure of a remnant.

The following procedure is adopted in the investigation of a rockburst.

(1) The team of specialists visit the site shortly after the event. The damage to the excavation and sup-

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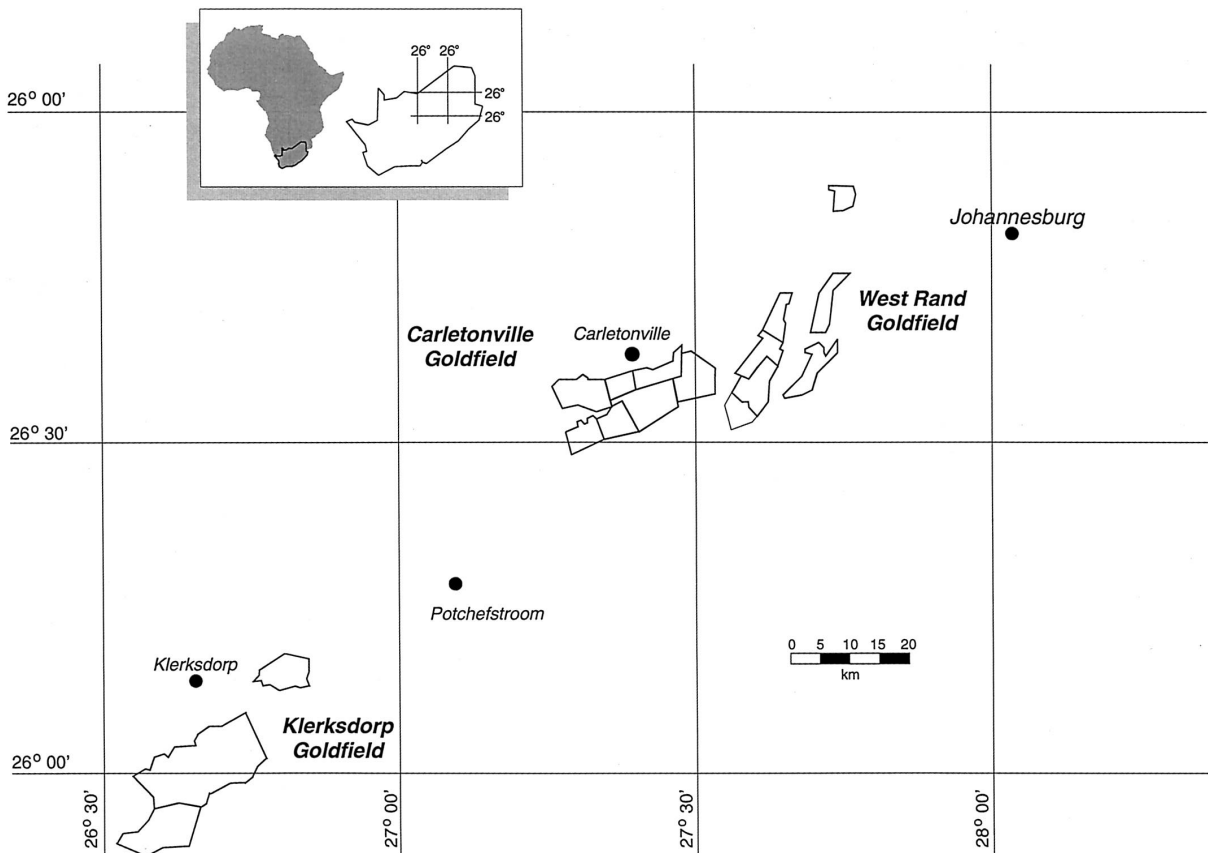


Fig. 1. Map showing the location of the Carletonville Goldfield, South Africa. The rockburst which took place on 4 May 1994 occurred on a mine in this goldfield.

port elements is carefully studied, dynamic closure is estimated, and mining-induced fractures, joints and other geological features are recorded. Interviews are held with witnesses of the rockburst and rock engineering staff at the mine. Each member of the team has a good general knowledge of rock engineering and mining in addition to an area of expertise. In the investigation described here, the team consisted of two seismologists, a mining engineer, a rock mechanics practitioner, and a geologist. The site was visited on two occasions by the team.

(2) Seismograms are inspected to determine the source parameters. The seismic history of the surrounding area and relevant structures is assessed.

(3) Numerical modelling is used to evaluate the mining layout and sequence at the time of the rockburst by calculating parameters such as energy release rate and excess shear stress.

(4) Support elements such as hydraulic props and tendons may be recovered from the rockburst site and tested in the laboratory.

(5) Rock samples may be collected and the properties of the strata in close proximity to the rockburst site determined.

(6) Future mining strategies are investigated and recommendations formulated.

## 2. Geological setting

The VCR is a gold-bearing placer deposit that was preserved by the eruption of the lavas of the Ventersdorp Supergroup, some 2700 million years ago (Armstrong et al., 1991). Several features (e.g. rolling of the orebody due to pronounced topographic variations at the time of deposition, mode of mineralisation, and preservation by volcanic rocks)

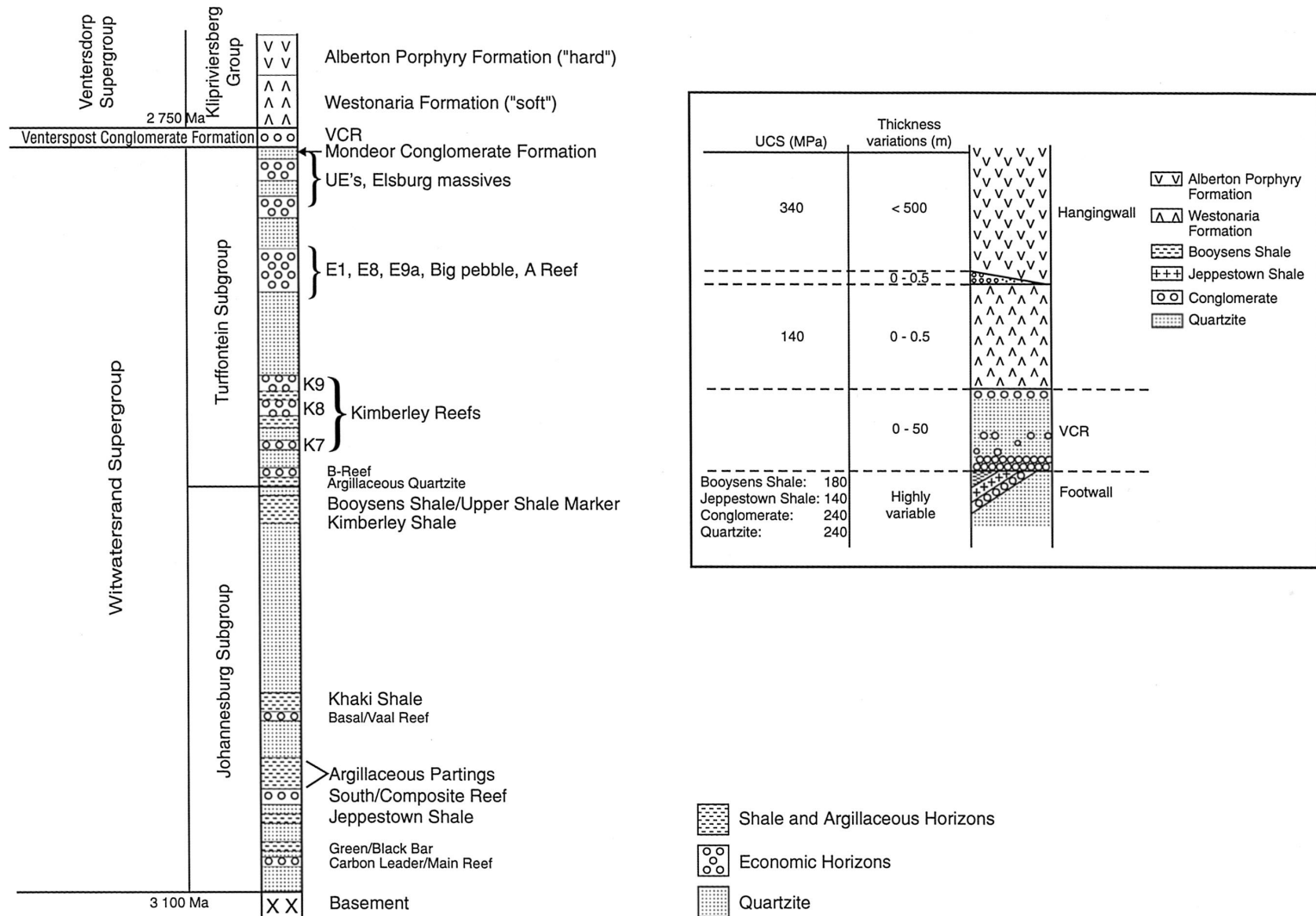


Fig. 2. Idealised stratigraphic column through the Witwatersrand Basin with an insert providing detail of strata associated with the Ventrersdorp Contact Reef. The slope damaged by the rockburst was mining the Ventrersdorp Contact Reef (VCR), which forms part of the Ventrerspost Conglomerate Formation.

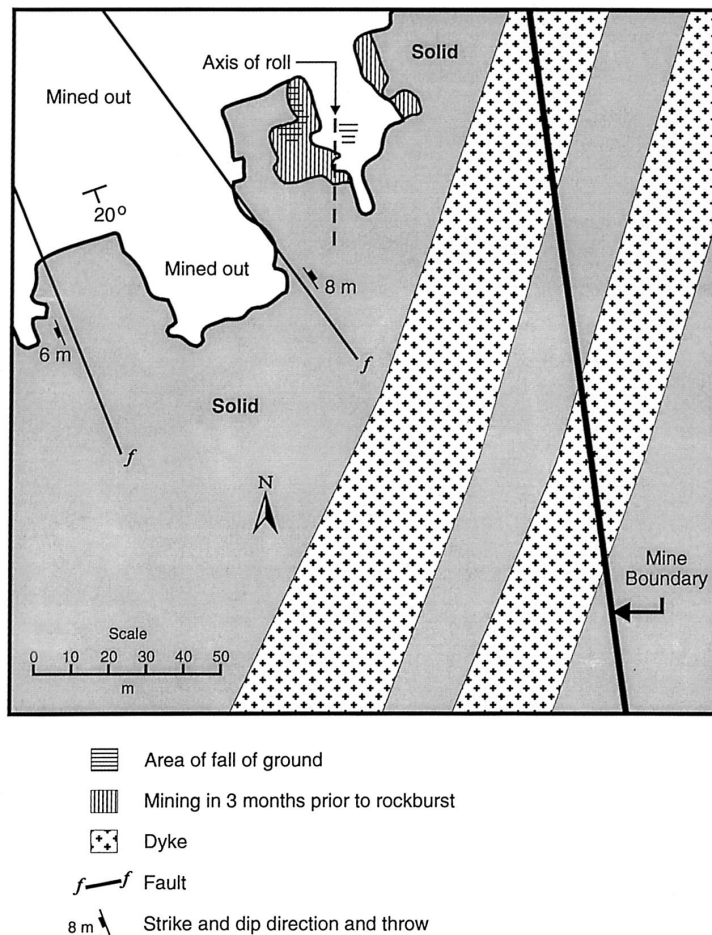


Fig. 3. Plan of a portion of the gold mine in the Carletonville gold mining district showing the site of the rockburst of 4 May 1994 and major geological features. Stopping during the 3 months preceding the rockburst is indicated by vertical hatching. The working place is 2300 m below the surface.

distinguish the VCR from the underlying, older Witwatersrand gold deposits. This led SACS (1980) to include the VCR in the Venterspost Conglomerate Formation which separates the predominantly sedimentary Witwatersrand Supergroup and the predominantly volcanic Ventersdorp Supergroup (Fig. 2). The VCR currently produces about 18% of the gold mined in South Africa.

In the area of the rockburst (Fig. 3) the VCR is a 1–2-m-thick clast- to matrix-supported conglomerate intercalated with minor quartzite, dipping to the south at 20°. Volcanic rocks of the Alberton Porphyry Formation (known informally as the ‘hard lava’ and part of the Ventersdorp Supergroup) overlie the VCR. The VCR is underlain by quartzites

and conglomerates of the Mondeor Conglomerate Formation. The angle of unconformity between the VCR and the underlying, subcropping rocks is about 4°. Abrupt variations in strike, and especially dip, are frequently encountered during the mining of the VCR. These variations are loosely termed ‘rolls’. Rolls reflect topographic variations of the palaeosurface, marking the transition from terraces to slopes, or channels to overbanks (e.g. Schweitzer et al., 1993; McWha, 1994; Henning et al., 1994). These features are particularly hazardous during mining (J. Hamman, pers. commun., 1993).

Shear planes parallel to the bedding have been documented within the footwall strata. Faulting is most pronounced subparallel to the VCR plane.

These fault planes commonly undulate, crossing the boundary of different strata, and are frequently observed in the vicinity of the contact between the VCR and lava. Bad hangingwall conditions are generally encountered in these areas.

The joint orientation is variable, with N–S and NNE–SSW being the dominant strike directions, parallel to the orientation of the major faults and dykes. Faults and dykes running in a NW–SE direction are less common. Throws along faults may vary from a few metres to tens of metres. Joints dip steeply towards the east or west. A dyke, positioned in unmined ground within 40 m of the rockburst site, has a NNE–SSW orientation.

### 3. Observations at the rockburst site

The peninsular remnant was formed as the result of geological features encountered during mining (see Fig. 3). A stope, mining in an easterly direction, encountered a fault with an 8 m downthrow to the east. Consequently a new crosscut was developed and stoping recommenced. The face being mined in a westerly direction encountered a roll, which displaced the reef downwards by about 2 m resulting in mining progressing into the hangingwall. A trench was excavated to reestablish mining on the reef horizon. Stoping from the trench proceeded initially towards the west, followed by northward mining. Fig. 4 is a plan showing the position of the roll, the type of support installed at the time of the rockburst, and the extent of the fall of ground. A strike section through the rockburst site is shown in Fig. 5.

The fault plane forming the western boundary of the remnant has been exposed by mining. No evidence of recent movement related to the seismic event was detected. Fresh timber was exposed in a gully pack (point A, Fig. 6), suggesting that dynamic loading had caused coseismic convergence of 5–10 cm. Some of the packs in the siding down dip of the upper strike gully (between C and E, Fig. 6) had been pushed into the gully by broken rock ejected from the exposed down dip face. Between C, D and E dynamic loading caused some damage to packs with an estimated dynamic convergence of 10–15 cm.

The face mining the F–G panel had been stopped as the reef rolled down towards the west. A line of timber packs had been installed parallel to the face

from F to G. At the top of the panel (position F) reef was exposed at the base of the face, but over the remainder of the panel only lava was exposed. Between F and G rock had been ejected into the void between the original face position and the first dip line of packs. Typical of a face burst, no hangingwall had fallen. Bulked face and footwall rock had been ejected into the void between the (original) face position and the dip line of packs (Fig. 7). Fresh splitting on packs in this area indicated dynamic convergence of 10–15 cm, and smears of timber on the hangingwall provided evidence that packs were forced laterally by the ejection of the face.

The mining-induced extension fracturing in the stope exhibits features typical of VCR areas where quartzite–conglomerate and hard lava form the footwall and hangingwall of the orebody. Flat fracturing occurs within the hangingwall lavas, while steep fractures are encountered in the footwall.

Severe damage occurred at the updip face (H, Fig. 6). The hangingwall of the updip stope was shattered into small fragments. The support that had been installed (1.1 × 1.1 m timber packs and hydraulic props at the face) was ineffective in supporting this hangingwall. The strata in this area were structurally disturbed by the reef roll and an undulating, bedding-parallel fault. To the east of the roll the fault plane was located close to the VCR–lava contact. To the west of the roll the fault plane is found within the hangingwall lava about 2 m above the VCR–lava contact (Fig. 5). This phenomenon has been observed at VCR rolls at other mines, where the bedding-parallel fault does not follow the VCR–lava contact when straddling rolls. Towards the west of the roll the undulating fault plane marks the top of the fall of ground area (Figs. 5 and 8). The bedding-parallel fault and minor fault planes associated with the major fault are coated by calcite. Minor faults and randomly oriented joints, associated with secondary calcite, are most prominent in the vicinity of the roll and appear to decrease in abundance with increasing distance away from the roll. The presence of the calcite-coated joints and minor faults weakens the hangingwall.

A large amount of rock was shaken from the roof at position I (Fig. 6), burying a winch, which was fortunately not being operated at the time of the rockburst.

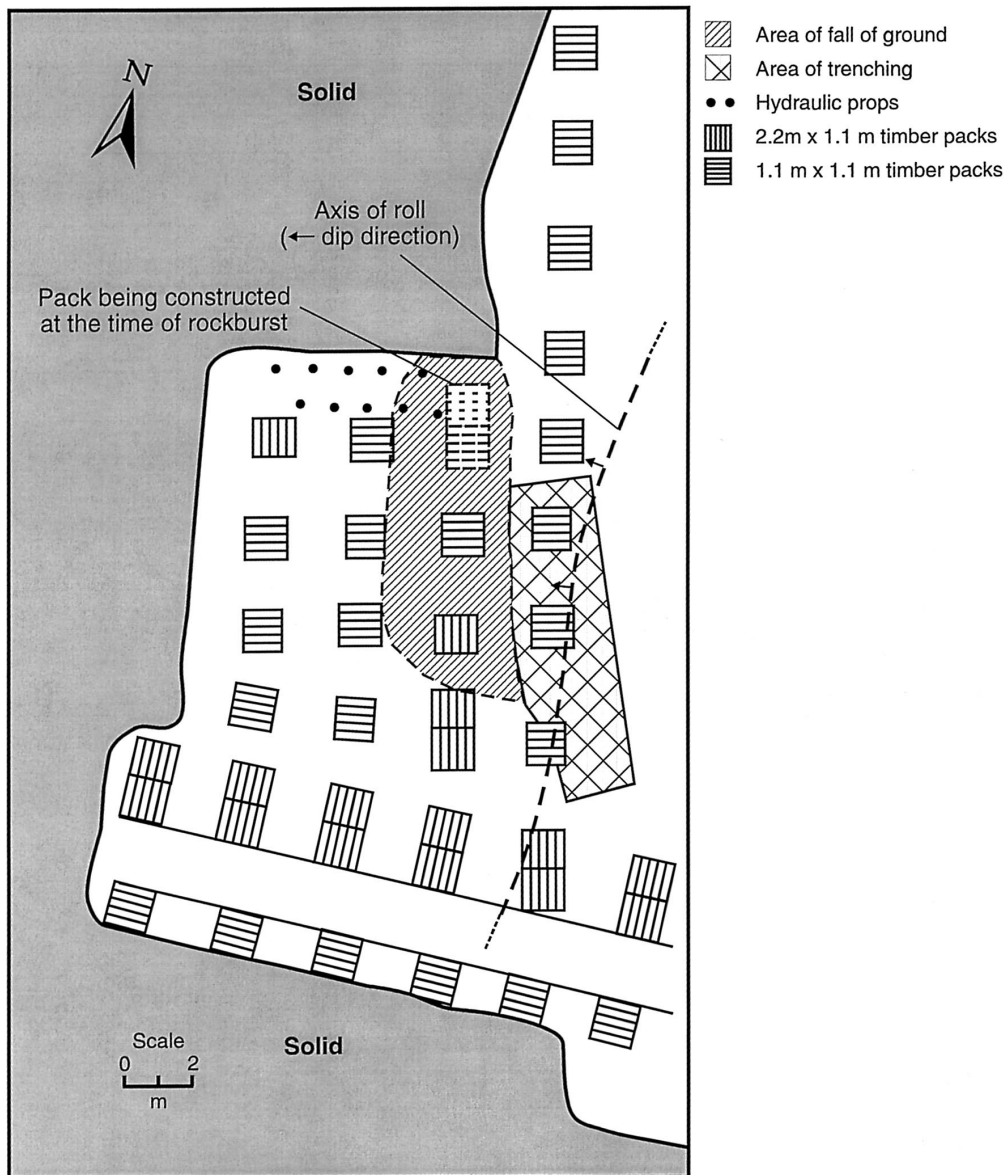


Fig. 4. Plan showing the support installed in the working place at the time of the rockburst, the extent of the fall of ground, and the area of the trench which was excavated to negotiate the 'roll' in the orebody.

#### 4. Rockburst mechanism

The focus of the rockburst was close to the eastern boundary of the mine (Fig. 3), outside the mine seismic network, resulting in poor location accuracy. Consequently, it was not possible to determine from the seismograms alone whether the focus of the rockburst was associated with slip along the

proximal dyke or failure of the peninsular remnant.

Calculations were made to determine whether it was feasible for failure of the remnant to release sufficient energy to produce a magnitude 2.1 event. The greatest uncertainty in making this calculation is the estimate of the volume of convergence. However, it was possible to get a fairly reliable estimate from

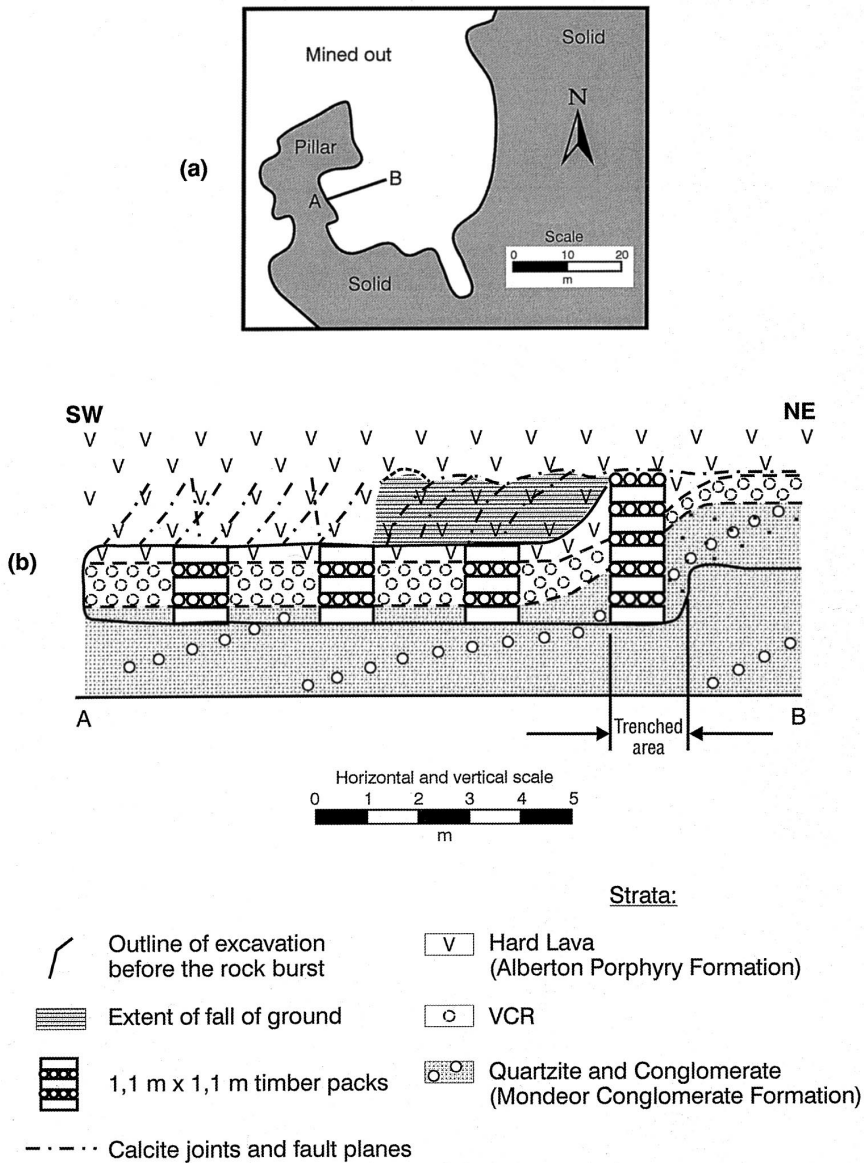


Fig. 5. Strike section through the working place showing geological features and timber packs.

observations of the damage to packs surrounding the remnant. The fractured perimeter of the remnant was excluded when estimating the area of the remnant which could have stored the elastic energy released by the rockburst. The following parameters were used in the calculation:

Area of 'elastic' pillar                    300 m<sup>2</sup>  
 Convergence                                    10 cm

$\Delta V_c$  (volume of convergence)    30 m<sup>3</sup>  
 $G$  (rigidity modulus of quartzite) 40 GPa

The seismic moment was estimated using the equation from McGarr and Wiebols (1977):

$$M_0 = G\Delta V_c = 1.2 \times 10^{12} \text{ Nm}$$

The magnitude of the event was then estimated using the Hanks and Kanamori (1979) moment mag-

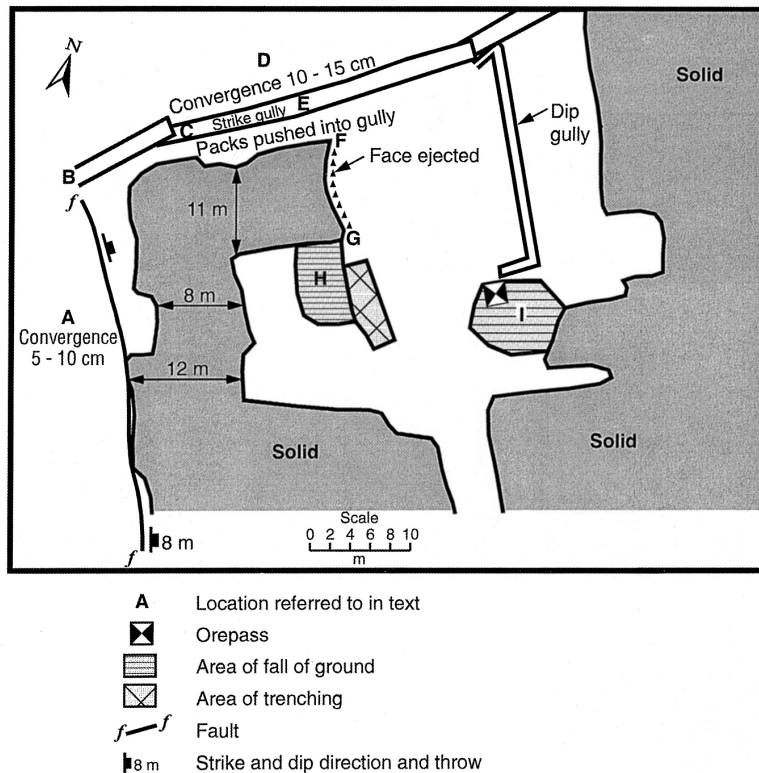


Fig. 6. Plan of the stope showing the positions of observations described in the text.

nitude relationship:

$$\log_{10} M_0 = 1.5 M + 9.1$$

thus

$$M = (12.08 - 9.1)/1.5 = 2.0$$

which is in remarkably good agreement with the observed magnitude of  $M = 2.1$ . To give some indication of the sensitivity of this calculation to the assumptions made above, the calculation was repeated assuming a volume of convergence of only  $15 \text{ m}^3$ . A magnitude  $M = 1.8$  is obtained.

On the basis of the above calculations and the decrease in the coseismic stope closure away from the peninsular remnant, it was concluded that the source mechanism was failure of the remnant rather than slip along the dyke. Several other factors have been identified which may have given the peninsular remnant a predisposition to fail violently and the hangingwall to fragment when subjected to violent shaking.

(1) The stoping layout resulted in an L-shaped

peninsular remnant. At the time of the rockburst the width of the remnant ranged from 8–12 m (see Fig. 6). If the strength of one limb of the remnant was exceeded, it is likely that the entire remnant would have failed simultaneously. In contrast, a stoping layout giving rise to a triangular-shaped remnant would tend to fail at the apices of the triangle, with the core remaining intact.

(2) Width: height ratio is a design criterion used to predict pillar performance. If the ratio becomes small, the pillar is in danger of crushing. With a pillar width of 8–12 m and an average stoping height in the area of 1.6 m, the nominal width: height ratio was about 6 at the time of the rockburst. Trenching carried out in order to establish the face to the west of the 2 m roll increased the height over which the southeastern sector of the remnant was unconfined. A similar effect may have been produced by the up-dip strike gully. Fissile or weak partings, such as the bedding-parallel faults, may also increase the effective 'height' of a pillar (COMRO, 1988, p. 87). Due





Fig. 7. Rock ejected from the footwall and face between F and G (Fig. 6) into the space between the original face position and the first dip line of packs. The photograph is taken looking updip with the face to the left. Note the intact hangingwall.

to trenching and partings the effective width:height ratio may have been considerably smaller, resulting in a potentially unstable configuration.

(3) The rock type exposed by stoping around the peninsular remnant is mostly the hangingwall lava. Referring to Fig. 6, the hangingwall lava is exposed from A to B due to the fault with an 8 m downthrow to the east; the lava is exposed between B and F as the downdip siding of the strike gully does not follow the 20° dip of the reef; while from F to G the lava is predominantly exposed due to the stoping overshooting the 2 m roll. Recent measurements indicate that the lava hangingwall and VCR have similar values of Young's modulus (about 80 GPa). However, the unconfined compressive strength (UCS) of the hard Alberton lava (>250 MPa) is substantially greater than that of the VCR conglomerate (>180 MPa), and consequently can store more elastic energy. Should a lava remnant fail, it will do so more violently than in the case where the remnant is comprised of conglomerate.

(4) The numerous calcite-coated joint planes found in the hangingwall in the vicinity of the roll indicate that the rock forming the brow was weak and prone to fragmentation during violent shaking.

## 5. Support behaviour

Rockburst statistics show that 90% of the rockburst fatalities occurring in Ventersdorp Contact Reef (VCR) stopes are caused by ejected rock less than 1.6 m in thickness (Roberts, 1995). The thickness of the fall of ground described in this paper was about 1.3 m. Rockburst-resistant support systems should be capable of supporting hangingwall slabs of this thickness, but failed to do so. Clearly the study of the performance of support under rockburst conditions is of crucial importance.

The support system in the working place consisted of 1.1 × 1.1 m timber packs and hydraulic props with headboards at the face (Fig. 4). Although many of the hydraulic props had been removed after



Fig. 8. Photo mosaic showing the up-dip face where the fatalities occurred, viewed from position H (Fig. 6) and looking up-dip. The timber packs on the right are situated to the east of the roll. The hangingwall fragmented during the rockburst. Most of the fallen rock was subsequently removed. Note the numerous fractures and joints in the face, and the smooth surface marking the parting above the collapsed brow.

the rockburst, examination of the remaining props showed clearly that the props had been ineffective in preventing falls of ground. This is ascribed to the fragmentation of the hangingwall. The timber pack underneath the brow at H (Fig. 6) was well installed, but did not hold the brow up. From Fig. 5 it is clear that no horizontal confinement is provided, without which a brow is prone to disintegrate. The rockbolts installed in the vicinity of the crosscut-reef intersection (position I) were also ineffective in preventing shake out of the fractured hangingwall by the rockburst.

## 6. Seismicity

Seismic data are available from the beginning of 1984 to the time of the rockburst. Fairly detailed seismic coverage only commenced in 1987, and continuous cover exists only from the start of 1989. There has been no significant change in the general

level of seismicity since the establishment of the mine seismic network in 1989. The majority of seismic events are located close to the mining face, although some events have occurred in back areas. The magnitude of the seismic event investigated was not unusually large; during the 11 year period (1984 to 1994) about 400 events with a local magnitude greater than 2 have been recorded. Larger events ( $M \geq 2.5$ ) are not evenly distributed over the mining area, but are prevalent in the eastern part of the mine.

## 7. Mining geometry

The elastic modelling program MINSIM-D, which employs the boundary element method, is routinely used to evaluate layouts and sequences for the mining of tabular orebodies such as those encountered in the Witwatersrand Basin of South Africa (Napier and Stephenson, 1987). MINSIM-D was used to calculate the theoretical stresses in the

rock mass using the mining layout at the time of the rockburst. The principal stresses on the dyke were low (85–95 MPa) and the changes in the stress are small (less than 2 MPa), indicating that failure of the dyke was unlikely.

The energy release rate (ERR) values on the advancing faces were also low ( $<20 \text{ MJ/m}^2$ ) due to the limited mining span. The stresses normal to the reef plane reach values exceeding 500 MPa on the perimeter of the remnant. However, these values are derived from an elastic analysis. In practice the rocks in these areas would have been crushed, and the load transferred to the interior of the remnant. Average pillar stresses (APS) within the remnant were calculated to be in the range of 150–250 MPa at the start of mining, increasing to 200–350 MPa at the time of the rockburst. Considering a value of 180 MPa to be the minimum UCS value of the host rock, the APS:UCS ratio is less than 1.6. This is safely below the limit of 2.5 given by COMRO (1988, p. 87) for a pillar with a width:height ratio greater than 10. However, it is important to realise that rock ahead of deep-level mining faces is intensely fractured to a depth of 2 m or more and would carry a load very much less than the UCS. Taking the fractured zone into consideration, the effective width of the remnant is substantially reduced. The stress in the core of the remnant could be increased to 500–550 MPa, a point where failure is likely.

## 8. Conclusions

The source mechanism of the magnitude 2.1 rockburst which occurred at 9h49 on 4 May 1994 is considered to be due to the failure of the peninsular remnant and not slip on the dyke or on the 8 m fault. There has been no significant change in the general level of seismicity in the 5 years preceding the rockburst. The majority of events are located close to the mining face. Events with local magnitude exceeding 2 are not unusual on the mine, occurring almost weekly on average.

Two different rockburst damage mechanisms were identified. The face and footwall on the east side of the remnant were violently ejected into the void between the original face and first line of timber packs following failure and dilation of the remnant and its foundation. The damage observed on the south side

of the remnant had a different mechanism. The hangingwall was weak due to the presence of a bedding-parallel fault and associated calcite-coated joints in the vicinity of a roll in the orebody. The hangingwall fragmented and collapsed due to the shaking associated with the seismic event and dilation of the remnant. The peninsular remnant was particularly vulnerable to rockbursting due to its L-shaped geometry, a high effective unconfined height (due to trenching and bedding-parallel faulting), and a weak hangingwall (due to faults and joints in the vicinity of the roll of the reef). A stoping layout giving rise to a triangular-shaped remnant with the face advancing towards the unmined ground to the south is preferable, as failure would tend to occur at the apices of the triangle, with the core remaining intact.

Elastic modelling does not indicate any significant transfer of stress onto the dyke, nor does it suggest immediate failure of the remnant. However, if the reduction in the effective width of the remnant due to fracturing ahead of the face is taken into account, the effective stress in the core of the remnant is increased to 500–550 MPa. Failure is likely at these stress levels.

The stope support system (timber packs and hydraulic props) was ineffective in preventing falls of ground due to the fragmentation of the hangingwall. Larger headboards should be fitted to hydraulic props in areas where the hangingwall is prone to fragmentation. The lack of support providing horizontal confinement to the brow probably increased its susceptibility to fragmentation.

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