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Nonlinear rock behaviour and its implications on deeper-level platinum mining

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Uniaxial tests performed on core from instrumented sites at Amandelbult 1 shaft, Impala 10 shaft and Union Section Spud-shaft showed a nonlinear elastic relationship between applied load and induced deformation. This nonlinear behaviour does not appear to be dependent on borehole orientation but in the case of the Amandelbult and Union sites appears to have been influenced by the stress condition of the rock mass at the time of drilling. Cores drilled at these two sites under destressed conditions, such as over a stope, showed a linear elastic response to the applied load whereas most of the cores drilled under relatively high radial stresses were nonlinear. The Impala 10 shaft tests, however, all showed strong nonlinear behaviour irrespective of the stress condition of the rock mass at the time of drilling, although high stress conditions may have influenced the severity of the nonlinearity. A comparison between underground stress change measurements and an elastic model indicated that the rock mass became nonlinear when the virgin stress condition was relaxed to about 10 MPa. The cores for laboratory testing were retrieved from vertical boreholes drilled up from the centre of a stope and from horizontal boreholes drilled over pillars and stopes at about 600 m, 1 100 m and 1 400 m below surface for the three sites respectively. The k-ratios under virgin conditions were estimated from sockets, modelling and stress measurements to be 1.0, 1.3, and 0.5 for the Amandelbult, Impala and Union sites respectively. Of the three sites, therefore, Impala 10-shaft appears to have had the highest virgin stress state. Tests performed on similar rocks from shallower depths at Impala Platinum essentially showed a linear relationship between stress and strain. From the small Impala Platinum rock test database available to the project, it appears that the nonlinear elastic behaviour initiates at this mine from about 1 000 m below surface and seems to become progressively more nonlinear below this depth. In addition, the nonlinear elastic rocks are weaker, have a lower Young's modulus and a higher Poisson's ratio than their linear elastic equivalents. Interestingly the tangential Poisson's ratios of the nonlinear elastic materials are often greater than 0.5 at 50% of the failure stress, suggesting an early failure initiation. The paper describes the microscope and modelling work done to determine the causes of the nonlinear behaviour and discusses some implications of the behaviour for deep-level mining.

Introduction

Approximately 100 uniaxial tests were performed on cores from vertical and horizontal boreholes drilled above pillars and above an open stope at Impala 10 shaft. The instrumentation site was about 1 100 m below surface and the k-ratio was estimated to be 1.3 from direct stress measurements and numerical modelling back-analysis. All the tests showed a strong nonlinear stress-strain relationship, which was observed at all borehole orientations, stress conditions of the rock mass at the time of drilling, and rock types. The results were compared to tests performed on similar rock types from instrumentation sites at Amandelbult 1 shaft and Union Section Spud shaft, at 600 m and 1 400 m below surface, respectively. It was established that cores retrieved under low stress conditions at these sites (destressed as a result of mining) were usually linear elastic, whereas cores drilled under high stress conditions were often nonlinear.

Thin sections from the Impala rocks were compared to linear samples of the same rock type from the Amandelbult and Union section sites. The behaviour could not be associated with a difference in mineral composition. Also, no correlation was found between the density of microfracturing and the nonlinearity of the stress-strain relationships. It was found through limited scanning electron microscope (SEM) investigations, however, that specimens that exhibited nonlinear behaviour contained open microcracks, whereas open microcracks could not be detected in specimens that exhibited a linear stress-strain relationship. Upon further investigation (on a limited number of tests), it was found that cores from Impala that were retrieved at depths of less than 1 000 m below surface did not demonstrate nonlinear behaviour. A literature review was conducted to determine whether this condition has been observed elsewhere and what could cause this condition.

Literature review

The review revealed that the presence of microcracks is generally associated with nonlinear elastic behaviour in brittle rock. Gradual closure of these cracks, in response to loading in compression, results in compaction and an associated increase in effective stiffness. A distinct difference between the tensile and compressive Young's modulus is associated with the presence of closed cracks, whereas a nonlinear elastic response is associated with the presence of open cracks. Walsh (1965) analyses the effect of individual cracks on the effective material stiffness, while Bristow (1960) and Kachanov (1992) use the concept of a crack density parameter. Carvalho *et al.* (1997) present unique experiments on artificially cracked aluminium plates. Their results showed good agreement with theoretical models, and they subsequently used the theory of non-interacting cracks to characterize microcracks in a charcoal granite. Using a simple FLAC model, it could be established that the two-dimensional theoretical model provided a good match with a numerical model of a closing crack.

Anelastic (time dependant) strain recovery (ASR) has been suggested as a method to determine *in situ* stresses (Lin *et al.*, 2006; Wang *et al.*, 1997; Barr and Hunt, 1999). The principle is based on the assumption that overcoring of stressed rock can lead to differential stress and strain relaxation. An unloaded specimen therefore contains residual stresses that can result in the formation or opening of microcracks. Relaxation of residual stresses may have a time-dependent component, whereby the rate of (anelastic) strain recovery decreases with time. Sakaguchi *et al.* (2002) investigated the stress concentrations associated with the overcoring process and they concluded that the tensile stresses induced near the end of a core stub play a major role in microfracturing in a rock core during stress relief. This is an important conclusion, as it may cause (additional) damage in a core and promote the strain relaxation process.

While it is obvious that the composition of a rock will affect its relaxation response, no practically relevant information could be found on the response of natural rocks. The exact mechanism(s) for microcracking upon relaxation have not been determined, but it has been established by Teufel (1989) and Wolter and Berchheimer (1989) that acoustic emissions could directly be related to the anelastic strain recovery process. In addition it was found by Teufel (1983, 1989) that seismic wave velocities could be correlated to the amount of anelastic strain recovered in any particular direction. These phenomena were interpreted as being caused by the generation of microcracks during anelastic strain recovery. Matsuki (1991) proposed a method for estimating three-dimensional *in situ* stresses based on anelastic strain recovery measurements. However, there are some practical complications that may affect the calibration of this method. Firstly, stress concentrations induced during the overcoring process could influence the micro fracturing. Secondly, there is typically a time delay between the onset of stress relaxation and the time that strains can be monitored and, finally, changes in temperature also need to be accounted for.

In the petroleum industry, considerable interest in the quality of core and coring-induced rock damage has led to investigations into strain relaxation. Holt *et al.* (2000) produced synthetic sandstones in order to simulate virgin conditions and to analyse the stress relaxation effects in a controlled manner. The synthetic sandstones are formed by allowing cementation to take place under stress. It is argued that this is representative of natural sandstone and that properties, such as the Kaiser effect, anelastic strain recovery and induced wave velocity anisotropy are observed with the synthetics. In the studies on synthetic sandstones, drilling effects could either be included or excluded by controlling the loading history.

The literature review, and the presence of the observed open cracks, led us to conclude that microcracking in response to stress relaxation can occur in Bushveld rocks. In the literature, considerable efforts have been made to analyse the anelastic part of the recovered strains. However, at this stage, it is not obvious that time-dependent processes are contributing to the strain recovery in the case of the Bushveld rocks. It is of course possible that the generation of microcracks is a direct response to the removal of the virgin *in situ* stresses and that time dependency plays only a marginal role. It is thus highly likely that the magnitude of virgin *in situ* stress determines the onset of microfracturing. The nonlinear behaviour observed in samples drilled under relatively high stress conditions at Amandelbult and Union Section suggests that the tensile stresses induced near the drill tip, as a result of the stress condition of the rock mass, may be assisting or even causing the opening of microcracks. Samples retrieved from the Impala site, however, showed a nonlinear stress-strain relationship even from areas destressed by mining. *In situ* stress change measurements at the site confirmed that fracturing or opening of existing fractures was occurring due to stress relaxation. Thus the laboratory test results from the Impala site were studied in detail and the results from the other two sites used for comparison.

Stress conditions near the tip of a drill bit

Tensile stresses develop in the core at the end of a borehole if the rock being drilled is compressed. The tensile stress distribution in the core is dependent on the ratio of stresses in the rock mass, orientated in the axial and radial directions of the borehole, and could vary as shown in Figure 1 ('A' and 'B') (Kaga *et al.*, 2003). Axi-symmetric FLAC modelling shows a direct correlation between the magnitudes of the lateral compressive stress and the induced tensile stress in the core. In the case of zero axial stress the induced tensile stress is approximately 15% of the radial stress.

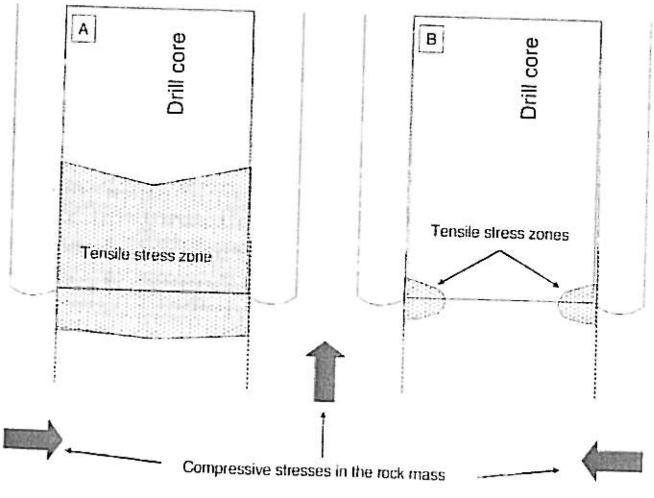

Figure 1. Schematic cross-sectional views of the tensile stress distributions in borehole cores drilled under low (A) and high (B) axial stress conditions (after Kaga *et al.*, 2003)

Nonlinear stress strain behaviour

Description of the site where the test samples were retrieved

The positions of the boreholes used to retrieve the test samples and to conduct stress measurements at the Impala 10 shaft site are shown in Figure 2. The dip of the strata is about 10° and the horizontal boreholes were mostly about 5° steeper than the strata. Samples were selected from above the stope and from above the pillars in the shallow-dipping boreholes. These samples were compared to the samples from the vertical boreholes.

Strain-stress behaviour under uniaxial loading

A typical example of the nonlinear strain-stress behaviour of samples from the Impala site is compared to the behaviour of the same rock type from shallow depth in Figure 3. Both cores were from vertically inclined boreholes but the shallower depth borehole was drilled from a haulage under virgin stress conditions and the deeper core was retrieved about 3 m above the centre of a stope, from Borehole Vert1 in Figure 2. Figure 3 shows that not only are the tangential modulus and Poisson's ratio affected, but the material strength is also reduced by the open microfractures. The curved shape and the significantly lower magnitude of the tangential modulus of the nonlinear material as shown in Figure 4 suggests that permanent damage initiates before the microcracks are closed. Figure 5 also demonstrates that an early onset of failure is associated with samples affected by microfracturing (1 100 m below surface). The early onset of failure is also an explanation for the observed lower strength of the microfractured material. The relatively large lateral (radial) strain in Figure 3 is explained by sliding on unfavourably orientated microcracks and resultant opening of wing-cracks, as illustrated in Figure 6.

The results of a limited number of uniaxial tests performed on spotted anorthosite from different depths across Impala Platinum Mine (Figure 7) show a distinct change in the stress-strain behaviour at a depth of about 1 000 m below surface. The severity of the nonlinear behaviour also appears to increase with depth below this point.

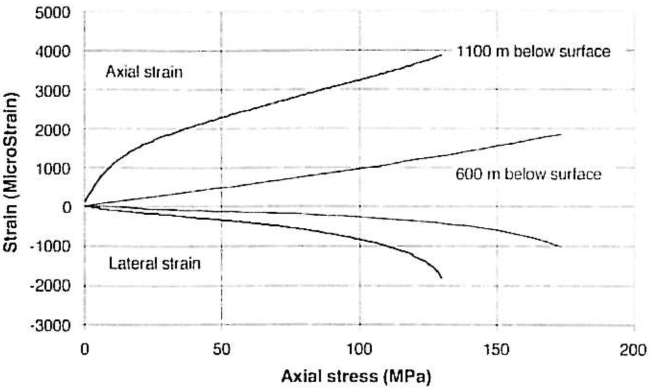

Figure 3. Strain-stress curves for spotted anothosite under uniaxial loading conditions from cores retrieved at 600 m and 1100 m below surface. Upper curves: axial strain, lower curves: lateral strain

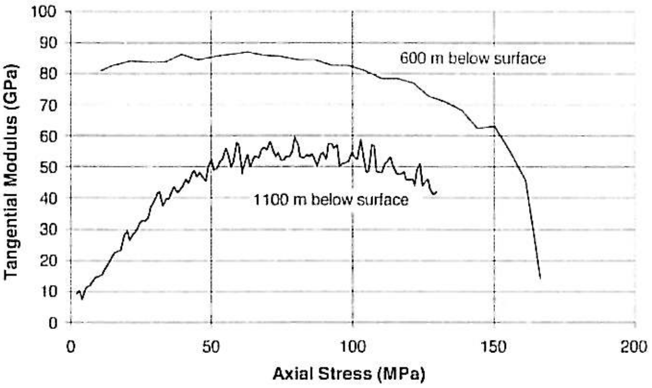

Figure 4. Comparison between the tangential modulus at 600 m and 1100 m below surface for anorthosite under uniaxial loading conditions

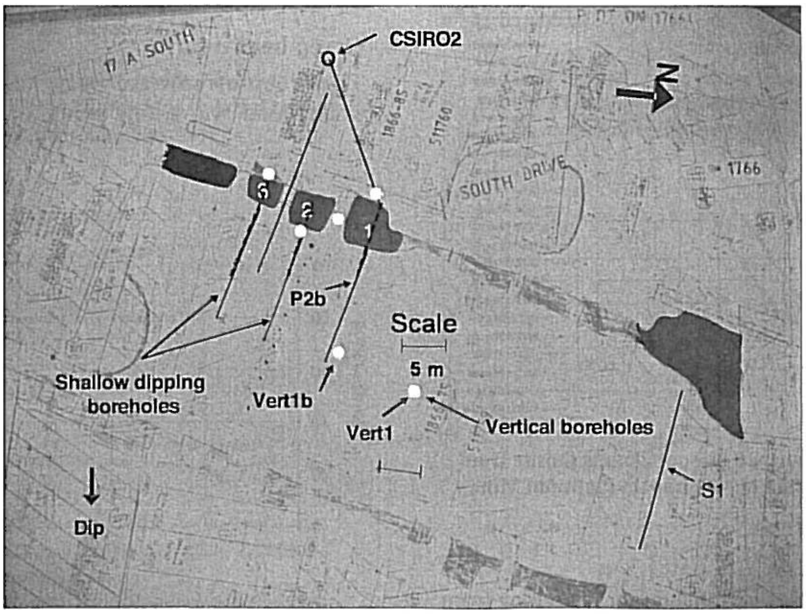

Figure 2. Stope sheet showing the positions of the boreholes at the Impala 10-shaft site

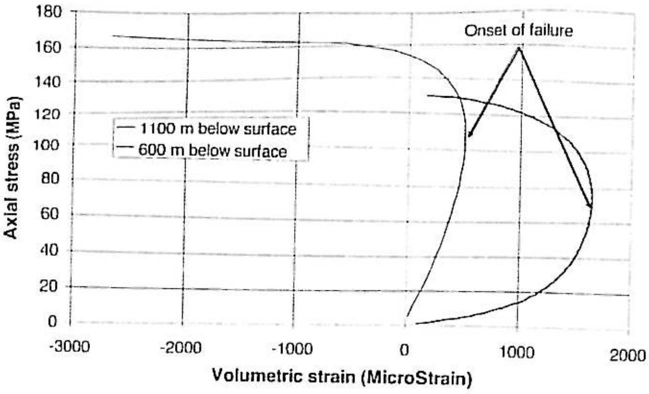

Figure 5. Volumetric strain-stress curves showing the onset of sample failure under uniaxial loading conditions

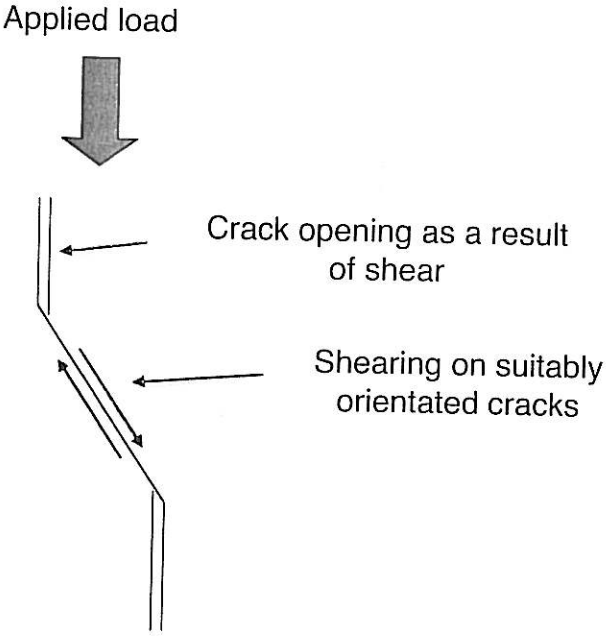

Figure 6. Lateral strain from shearing on microcracks and opening of wing-cracks

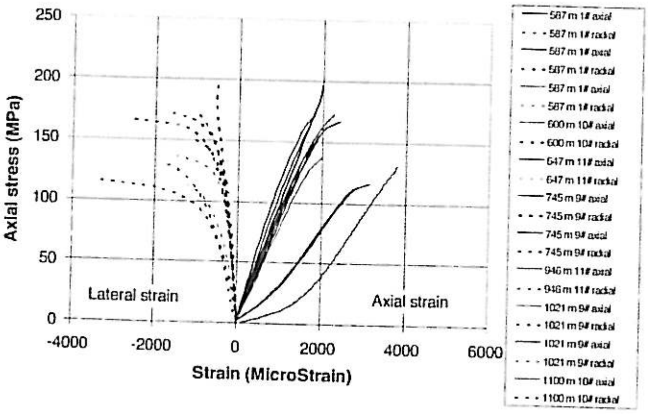

Figure 7. Uniaxial tests performed on spotted anorthosite from different depths below surface across Impala Platinum Mine

It is believed that the observed change in behaviour from linear elastic to nonlinear elastic is due to microscale stress differences that develop between crystals with different moduli when the virgin stress condition drops to some critical stress level. This does not cause microfracturing if the virgin stresses (i.e. the depth and k-ratio conditions) are less than some critical level.

Behaviour under uniaxial cycling

The graphs in Figure 8 show the applied stress vs. the monitored axial and lateral strains during five cycles of uniaxial loading and unloading on a cylindrical sample of spotted anorthosite, over a time span of one to three hours. The figure indicates that permanent, non-recoverable axial and lateral strain develops within each cycle. However, there is evidence (Hawkei *et al.*, 1973) that this strain may be reversible with sufficient time. The apparent permanent strains can be observed even at stress levels as low as 25 per cent of the peak strength. Interestingly, the non-recoverable lateral strains are greater than the corresponding axial strains. It should be noted that the rate of unloading was very slow compared to the loading rate.

The process of inelastic strain generation seems to be time dependent. This can be appreciated from Figure 8, where it can be seen how the lateral, and to a lesser degree, the axial strain, keeps increasing during very slow unloading. As the rate of unloading is far slower than the loading rate, it can be argued that the effect of the load has not fully been absorbed by the material at the onset of unloading. This absorption process therefore still continues during unloading and can be explained by the concept of sliding cracks. This mechanism would also explain the observed hysteresis. Triaxial tests performed on the WITS MTS machine at low confinement did not show a strain increase during unloading when there was a three-hour time delay between the loading and unloading cycle (Figure 9). However, it can be clearly observed that creep occurred during the three hours when the load was maintained at the maximum load. In addition, the very steep region at the start of the loading cycles in Figure 8 suggest that the shearing on microfractures had not fully reversed after the unloading cycle and that the socalled 'non-reversible' strain may have reversed if sufficient time had elapsed between the cycles. In essence, therefore the behaviour of the Impala anorthosite can be described as 'nonlinear elastic', with only a small degree of largely recoverable hysteresis.

Creep behaviour

The creep effects are best quantified by maintaining a steady load over a long period of time. Figure 10 shows the

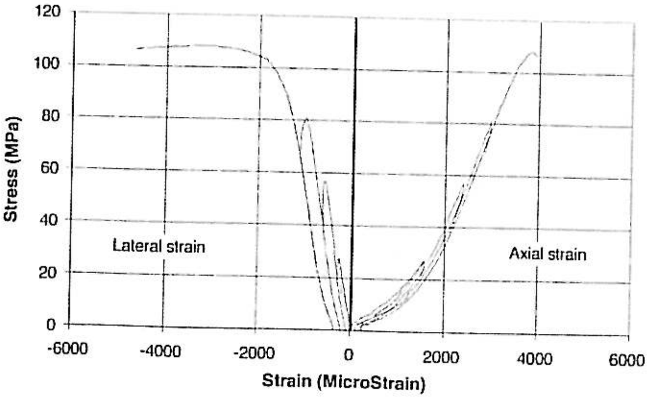

Figure 8. Cycles of loading followed by very slow unloading (KING machine, anorthosite)

result of a creep test on an anorthosite specimen that was subjected to an axial stress of 72 MPa and a confining stress of 1 MPa in the WITS MTS machine (same test as in Figure 9). The test lasted 3 hours, and suggests significant creep (in both the axial and lateral directions) within the first half hour of loading. However, creep continued to take place for the full three hours at a decelerated rate (steady state creep).

While the time-dependent strains in Figure 10 are relatively small compared to the total strain, they do seem to be associated with the nonlinear component of strain. It is of interest to note that both the axial (compressive) strain, as well as the lateral (dilatational strain) are affected. At this stage it is not clear if time-dependent effects are always associated with nonlinear behaviour. The observed creep in these uniaxial compressive tests can also not be used as an argument for creep behaviour during the relaxation process, when the microfractures are assumed to form. The possibility of anelastic strain recovery needs to be investigated in a different way.

Matrix elastic constants

Triaxial tests were conducted on anorthosite at a confinement of 30 MPa to determine the elastic properties of the material once the microcracks were closed, i.e. the 'matrix' elastic constants. The flattening of the curves in Figure 11 and Figure 12 were assumed to represent these values. The tangential modulus and Poisson's ratio of 83 GPa and 0.32, respectively, were thus calculated as the average of the values in these regions. These constants compared favourably with linear material uniaxial tests conducted on the same rock type at Amandelbult and Union Section. Of particular interest is the fact that the maximum tangential stiffness of around 83 GPa is reached when the applied stress reaches a magnitude of approximately 110 MPa. This would suggest that complete crack closure occurs only at stress levels that are far in excess of the *in situ* virgin stresses.

Characterization of the nonlinear behaviour

The nonlinear component of strain can be separated from the linear one with the use of the following equation, which is based on backfill 'hyperbolic' (Ryder and Jager, 2002) compaction of a porous material, and is similar to the compression behaviour of a joint under normal loading (Goodman *et al.*, 1968):

$$\varepsilon_n = \frac{b\sigma}{a+\sigma} \qquad [1]$$

where:

ε_n = the nonlinear strain component

σ = stress

b = maximum amount of inelastic strain that can be generated (total crack closure)

a = the stress at which half of the inelastic strain (b) is generated

By tuning the a and b value in Equation [1], a remarkably good fit can be obtained between the measured strains and

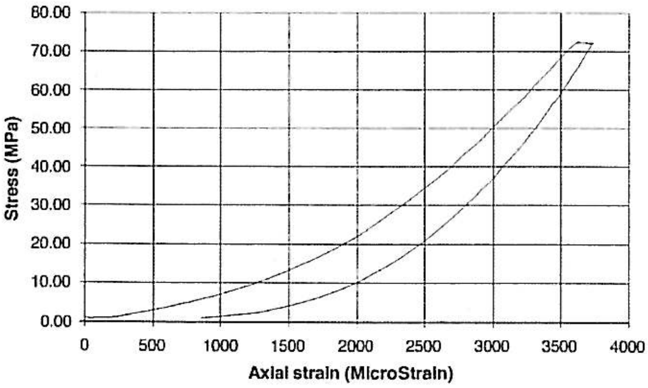

Figure 9. Cycle of loading and unloading with a delay of three hours between the cycle (WITS MTS machine, triaxial test with 1 MPa confinement, anorthosite)

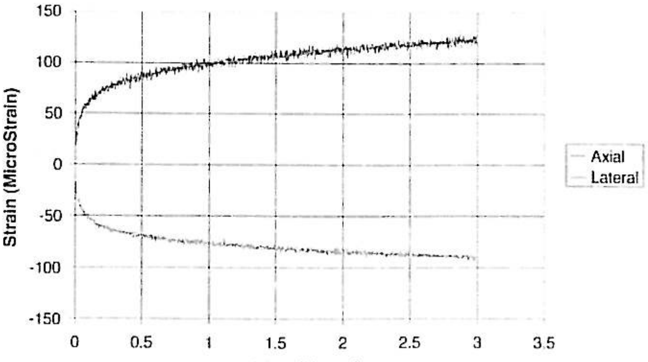

Figure 10. Creep test on anorthosite at triaxial stresses of 72 MPa at 1 MPa confinement

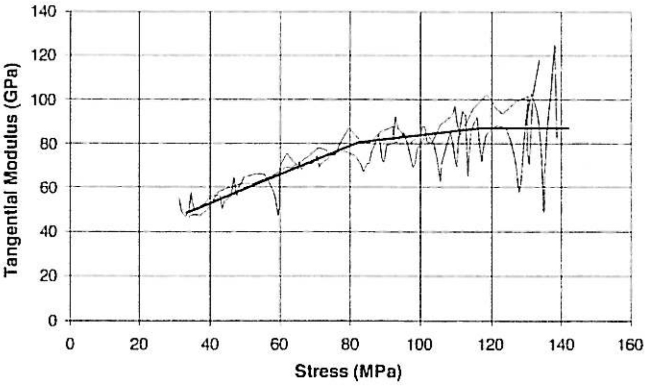

Figure 11. Tangential modulus as a function of axial stress, determined under triaxial loading conditions

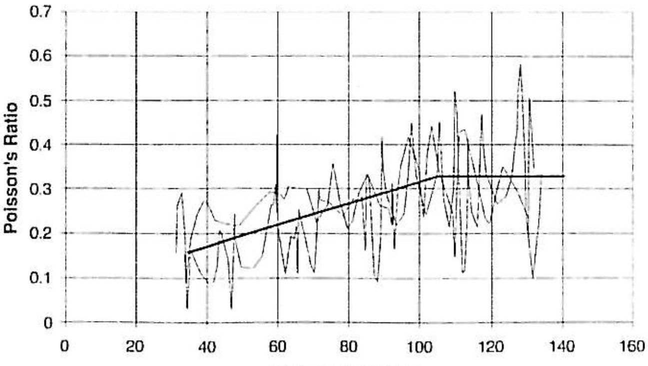

Figure 12. Tangential Poisson's ratio as a function of axial stress, determined under triaxial loading conditions

the strains calculated on the basis of Equation [1]. An example is shown in Figure 13. Note the unrealistically high Poisson's ratio (0.9) that was used to simulate the lateral strain, suggestive again of sliding cracks and opening of wing cracks.

Specialized tests to determine the rock mass behaviour

Hydrostatic loading conditions

Figure 14 shows the results of hydrostatic tests that were conducted on cores from a vertical and a horizontal borehole in the hangingwall (Vert1b and Horiz S1 in Figure 2 respectively). It can be observed that, in the case of the vertical hole, the axial strains are much larger than the lateral strains. The core from the horizontal hole, drilled under relatively distressed conditions, does not show a difference between axial and lateral strains. This observation of larger axial strains seems to confirm the hypothesis of drilling enhanced nonlinear behaviour by opening microcracks orientated in the lateral direction. The fact that this difference in strain is observed only in the vertical hole and not in the horizontal hole can be explained as follows: the horizontal borehole was located above a mined out stope at the time of overcoring. This implies that relatively small lateral stresses and relatively large axial stresses would be present around this borehole. Such a combination of stresses is not conducive to the formation of drilling-induced tensile stresses ('B' in Figure 1) and the associated enhancement of microfracturing. The core from the vertical borehole, on the other hand, was subjected to relatively large radial stresses (combination of both lateral directions) and a very low axial stress ('A' in Figure 1). The induced tensile stresses due to drilling are parallel to the axis of the core and therefore more likely to open lateral cracks. As the strains in the axial and lateral directions are the same for sample HorizS1, it appears that the drilling process had little or no effect on the behaviour of this sample. Thus the HorizS1 results and the good correlation between the lateral curve of Vert1b and the HorizS1 curves suggest a level of fracturing that is not affected by the drilling process and probably existed in the rock mass prior to drilling. Further evidence of the nonlinear material behaviour and the validity of the matrix constants was provided by an excellent match of Equation [1] to the data in Figure 14 using the matrix constants and relevant *a* and *b* values. The curved shapes of all the strain-stress relationships under the hydrostatic loading conditions in Figure 14 are indicative of open microcracks.

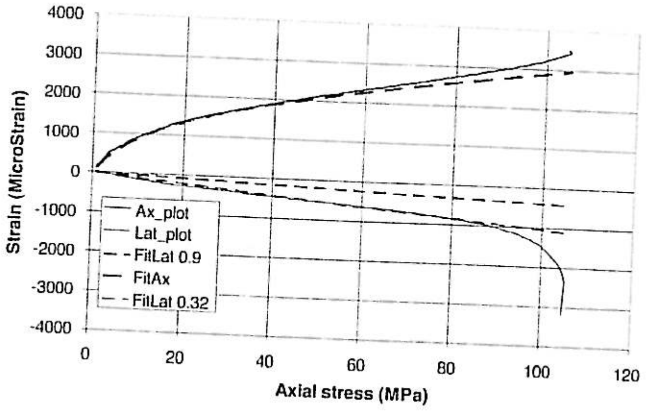

Figure 13. Strain-stress curves from a core extracted from a horizontal borehole (P1b in Figure 2) showing the fitted data determined from Equation 1 with $a = 15$ and $b = 1940$. The lateral plot was fitted using a Poisson's ratio of 0.9 and the plot for a Poison's ratio of 0.32 is also included for comparison

Biaxial loading conditions

Figure 15 shows the results from biaxial tests that were conducted on two cores similar to those two that were used in the hydrostatic tests. These tests show a similar nonlinear response in the lateral loading direction, as observed in the hydrostatic tests. The strain-stress behaviours in the lateral direction were also similar, which would be expected if the drilling process does not affect the microcracks in the axial direction. However, of interest here is the dilation in the unconfined axial direction. Relatively large axial dilation is associated again with the core from the vertical hangingwall borehole, which was drilled under relatively high radial (lateral) stress conditions. The large axial dilation in the core from the vertical hole is associated with pronounced hysteresis in response to the loading and unloading cycle. Some form of sliding and dissipation of (frictional) energy is assumed to be causing this response. The sliding cracks in turn will induce opening of cracks, and therefore dilation. Although less axial dilation was monitored in the other core, the elastic Poisson effect still does not account for their magnitude. Nonlinear deformations are therefore also affecting the dilation in those cases, most likely due to some internal sliding.

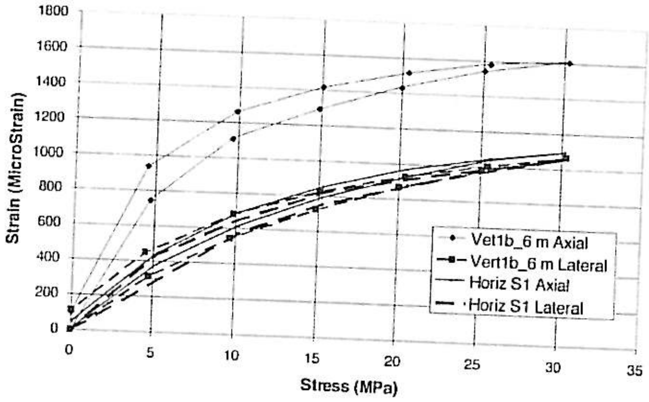

Figure 14. Strain-stress curves for hydrostatic tests performed on samples extracted under relatively higher (Vert1b – Figure 2) and lower (horiz S1 – Figure 2) *in situ* stress conditions

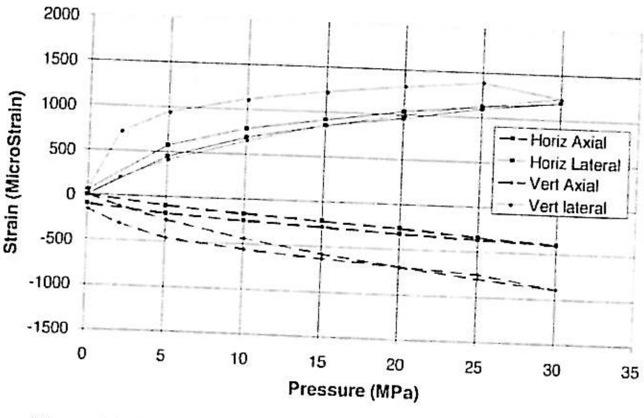

Figure 15. Strain stress results under lateral biaxial loading conditions from cores retrieved from vertical (Vert1b_4.83 m) and horizontal (Horiz S1) boreholes

Lateral tests

Uniaxial tests were conducted on smaller cores that were drilled across the original borehole cores, i.e. in a direction perpendicular to the original boreholes (Figure 16). The original cores were drilled under relatively high stress and the smaller cores were subsequently drilled under destressed conditions. Therefore no additional damage (drill induced) is to be expected in the smaller cores. The intention was to identify possible directional effects, by effectively loading in two orthogonal directions. For the purpose of comparison, the results of uniaxial tests, which were conducted on the original borehole core, are displayed in Figure 17.

A comparison between Figure 16 and Figure 17 shows that the small, lateral cores exhibited smaller axial strains than the original samples. Thus the cores that were drilled across the original cores were stiffer than the original cores. This would imply that the nonlinear component of strain is larger along the axis of the core irrespective of the direction of the borehole from which the cores are obtained. This conclusion is based on the assumption that the comparison is done on equivalent cores. It is, however, likely that variation in microcrack distribution affects the response of individual cores. In addition, there could be local variations within a single core specimen. As these tests were conducted on a very limited number of specimens, any conclusions based on comparing results from different cores need to be treated with caution. Testing the same specimen in different ways, such as was done in the hydrostatic, biaxial and uniaxial loading, provides more reliable information.

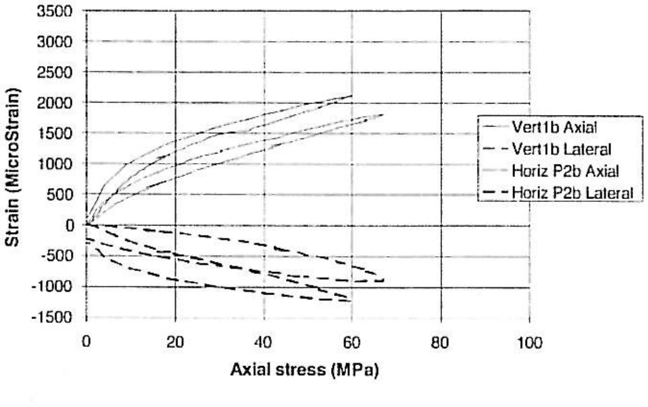

Figure 16. Results from tests on small cores drilled across the original borehole cores from Vert1b and Horiz P2b (Figure 2)

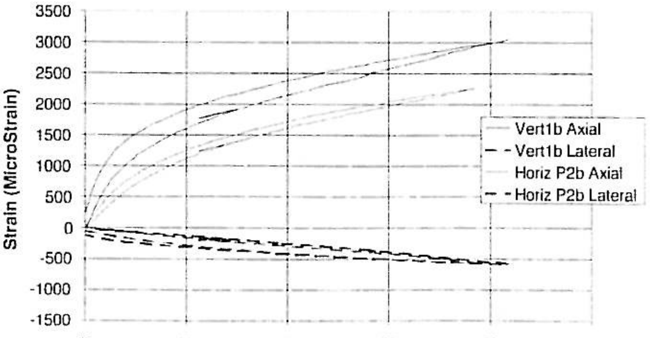

Figure 17. Result from tests on original cores

The results of the specialized tests suggest that the observed nonlinear behaviour is affected by the stress conditions under which the cores were drilled and provided some evidence of a pre-existing level of nonlinearity. However, the mechanism and conditions under which the microfractures open could not be established by these tests and underground instrumentation was therefore necessary.

Mechanism of microfracture opening at Impala Platinum

If it is assumed that microfractures open as a result of stress relaxation, then the immediate circumference and blind end of a borehole will be microfractured. Thus any gauges glued to a borehole for the purposes of stress measurements will be fixed to microfractured rock. A FLAC (Itasca, 1993) model was set up to establish the effects of such fracturing on permanent cells installed to measure stress change. (These cells were not overcored.) It was found that while the simulated stress in the locally micro-fractured rock is significantly lower than the stress in the surrounding unfractured rock mass, strain changes in the locally softened rock mass are hardly affected. Thus changes in stress can be determined by applying the matrix elastic constants to the measured strains, even if the rock mass is locally microfractured. A 3D stress cell was installed about 5 m above a panel and ahead of the face (CSIRO2 in Figure 2). The stress change measured in a vertical direction is compared to an elastic MinSim (COMRO, 1981) model in Figure 18. The good correlation between the measurements and the elastic model up to and just beyond peak stress suggests that the concept of using the matrix elastic constants to evaluate the stress change measurements up to a face advance of about 8 m ahead of the cell was correct. However, further face advances were associated with an inferred stress (strain) change much greater than suggested by MinSim. While the vertical stress suggested by MinSim is zero at 30 m face advance, the strain change measurements reflect a tensile stress of around -35 MPa. By comparing the MinSim results with the strain change measurements it is estimated that the deviation is initiated between a vertical stress of 10 MPa and 20 MPa. This deviation is believed to be associated with the microfracturing of the surrounding rock mass resulting from strain relaxation.

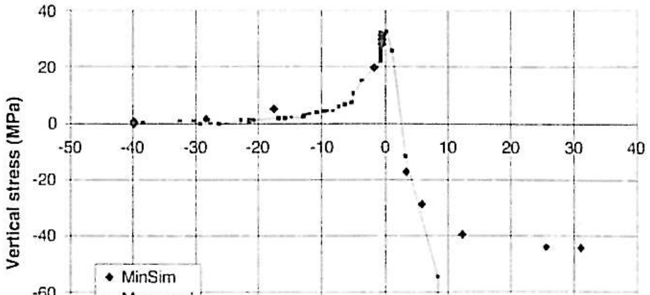

Figure 18. Vertical stress change in response to undermining at position CSIRO2 in Figure 2 compared to an elastic (MinSim) model. Negative face advance refers to the distance of the cell ahead of the face

Further evidence of the opening of microfractures in the rock mass was shown by stress change measurements conducted above the three highlighted pillars in Figure 2. An example of a sudden large inferred drop in stress to 'tensile' is shown in Figure 19. In this instance the stress drop was associated with a seismic event, which probably enhanced the microfracturing process in the rock mass around the borehole. The sudden inferred stress drop appears in most cases to occur at a vertical stress of about 10 MPa. In essence, a relaxation process is initiated and microfractures are opened. The associated monitored strains can not be used to infer real external stress changes. These observations have demonstrated that microdamage and associated nonlinearity (release of the 'b-component' of strain) can take place in response to the removal of *in situ* stresses. At the Impala site this appears to have occurred once the stresses dropped below about 10 MPa to 20 MPa.

Implications of nonlinear behaviour on mining at depth

The observed nonlinear behaviour is not just of academic interest, but also has certain practical implications:

- Stress measurements are directly affected and further investigations are required to determine evaluation procedures
- Deformations into the excavations will increase
- Seismic wave velocities and associated monitoring techniques will be affected
- There is a potential for strength reduction in rock that is subjected to strain relaxation
- There are implications for numerical models and
- The possible existence of a mechanism for horizontal fracture development in the stope hangingwall (at the interface between the softer microfractured material and the solid rock).

Conclusions and recommendations

Nonlinear strain relaxation is associated with microfracturing and appears to occur in Bushveld rocks under certain conditions. At Impala Platinum the behaviour appears to be present at depths below 1 000 m. Similar behaviour was also observed in some samples from the Amandelbult and Union Section sites. However, at these sites the condition appears to be induced under relatively high lateral stresses at the time of sample extraction. The stress condition at the time of sample extraction appears to be an important factor in determining the degree of nonlinear behaviour and is believed to enhance the nonlinear strain relaxation process in rocks that would normally show a linear strain response to stress. More testing is required to investigate this issue.

The observed nonlinear component matches the behaviour of typical porous materials. Based on available evidence, it can be argued that the onset of microfracturing is directly related to the magnitude of virgin *in situ* stresses. However, it was observed that complete microcrack closure only takes place at stresses that seem to be far in excess of the (assumed) virgin *in situ* stresses. This may also be related to the observed reduction in strength, as the presence of open microcracks can be expected to have a negative affect on the material coherence. It is currently not clear why the closure of microcracks is not accomplished when the applied stress levels are equal to the *in situ* virgin stress level. However, the phenomenon is suspected to be associated with shear along the crack planes and subsequent missmatch between opposing fracture planes. This issue requires further research.

Hysteresis and accompanying dilation, associated with cyclic loading and unloading, may be explained by sliding crack theory. Observations therefore suggest that the microfractures are not only subject to opening and closure, but also to sliding. Creep tests showed evidence of some time-dependent behaviour at compressive stresses that were well below the average strength of the tested specimens. While these results demonstrate the potential for time dependency, they do not prove that anelastic (time-dependent) strain recovery takes place during unloading. This issue needs to be investigated using acoustic monitoring techniques in conjunction with strain change measurements over time.

It is important that regions that are affected by the phenomenon of nonlinear strain relaxation are identified. The potential for strength reduction and fracture development needs to be properly quantified, as it could negatively affect stability in the deeper mines. The effects of microcracks on seismic wave velocities and associated seismic evaluations and stress measurements also need further investigations. Proper numerical simulations will need to account for the microfracturing and resultant softening of the rock mass around excavations.

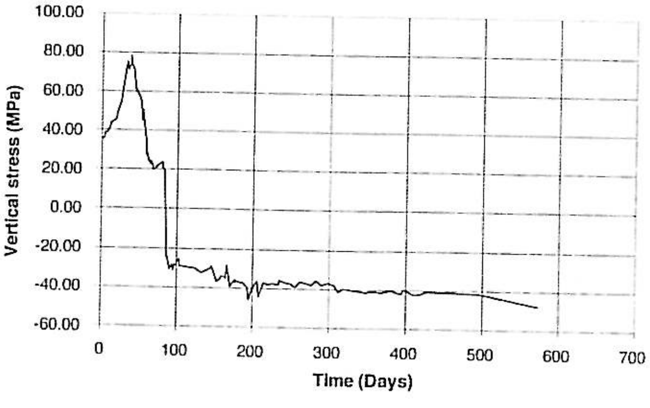

Figure 19. Absolute stress change measurement approximately 4.5 m above Pillar 2 (Figure 2), showing a fictitious stress drop at about 20 MPa

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References

BARR, S.P. and HUNT, D.P. Anelastic strain recovery and the Kaiser effect retention span in the Carnmenellis Granite, *U.K. Rock Mech. Rock Engng*, vol. 32, no. 3, 1999. pp. 169–193.

BRISTOW, J.R. Micro-cracks and the static and dynamic elastic constants of annealed and heavily cold-worked metals. *British J. Appl. J. Phys.*, vol. 11, 1960. pp. 81–85.

COMRO. MINSIM-D User's Manual, Chamber of Mines of South Africa, Johannesburg. 1981.

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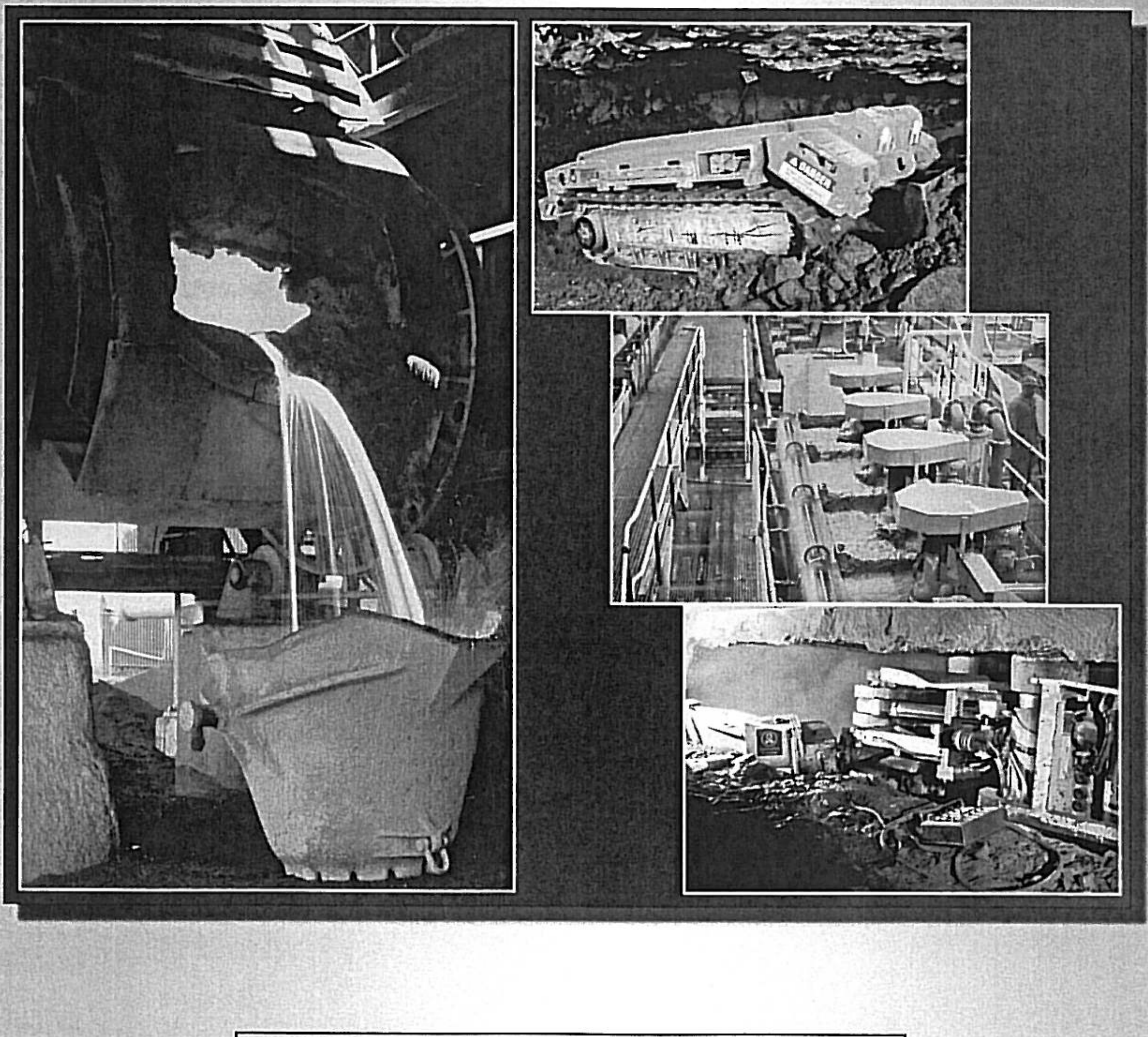

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FOREWORD

Platinum is a dynamic precious metal affecting many aspects of the global economy. The platinum market went from a supply surplus in 2006 to a deficit in 2007 and will most probably be in deficit again in 2008.The platinum price moved relentlessly higher during 2007 sparked by concerns of underproduction from South Africa.

Demand from the jewellery market fell only slightly in the face of the price rises, while healthy demand continued from the chemical, petroleum and electronics sectors. The new Exchange Traded Funds (ETFs) resulted in substantial demand from investors.

Supplies from South Africa fell by 260 000 ounces in 2007 to 5.04 million ounces. A wide range of challenges faced the industry, including safety, retention of skilled staff, industrial relations, and geological issues. While this cocktail of problems affected primary production at many mines, some mines reported increased platinum output on the back of successful expansion plans.

This was followed by severe power shortages, in January 2008, and ensuing power cuts, resulting in the temporary stoppage of deep-level mining operations.

Supplies from Russia, North America and Zimbabwe remained relatively unchanged in 2007.

In South Africa production is expected to grow from existing producers as brownfields expansions are commissioned. Three new mines, Blue Ridge, Smokey Hills and Platmin's Pilanesberg are due to come on stream in 2008. In addition, at least another six potential mining projects are in the feasibility study stage.

Increased metal prices, BEE rules and the redistribution of some mineral rights have encouraged a proliferation of companies exploring for and producing platinum across South Africa. Announcements of various BEE deals also look set to create a further wave of producers in the medium term.

It is against this background that the Third International Platinum Conference will address orebody delineation, project valuation and management, mine design and modernisation, mineral beneficiation and the market. It is also anticipated that the issue of safe production and overall increases in productivity, through the introduction of technology, will demonstrate Southern Africa's status as a premier mining country.

It is my pleasure to welcome delegates from abroad and locally, on behalf of the SAIMM, to the Third International Platinum Conference 'Platinum In Transformation'.

I trust that you will find the proceedings informative and value adding and will participate in the discussions and debate in order to obtain maximum benefit from the conference. I am sure that the social programme and post-conference tours will be interesting and of great benefit to participants.

Finally, a big word of thanks to the members of the Organising Committee, the management and staff of the SAIMM, and to our willing sponsors, without all of whom this conference would not have been possible.

Mike Rogers
Chairman, Organising Committee