In-situ measurements of pillar and rockmass behaviour in a moderately deep hard-rock mine

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Synopsis

An in-situ *experimental programme was carried out to improve the understanding of the rockmass and pillar behaviour in moderately deep hard-rock mines. The experiments were carried out at Impala Platinum mines and consisted of precise levelling measurements in the footwall of the reef, stress measurements in pillars, convergence measurements in the stope, and petroscope observations in pillars. The results were analysed using a computer program in an attempt to quantify the characteristic behaviour of the rockmass as well as the pillars. The measured off-reef displacement data were found to conform to the trends obtained from elastic modelling and the correlation could be improved by modelling the small pillars with reduced modulus to simulate 'yielding' of the pillars. The stress-strain curve obtained from analysing the* in-situ *results, showed*

Introduction

Like the other mines operating in the Bushveld Igneous Complex (BIC), Impala Platinum uses systematically designed pillar systems for support purposes. The need for using pillars is mainly due to the shallowness of the mining operations where, unless the hangingwall is adequately supported, vertical tensile stresses therein can lead to large falls of grounds and back-breaks.

The designs of pillar systems in the BIC vary, even between neighbouring mines, despite the similarities in geology and depth of mining. This appears to be due to each mine developing its pillar design methods mainly on the basis of practical experience. These empirically evolved design methods, although successfully implemented in general, cannot always provide answers to the problems with regard to mining in new ground or extending mining to greater depths.

This study was undertaken with the objective of obtaining further information on the current rockmass and pillar behaviour at Impala Platinum Mines. A system of underground experiments was planned and executed to measure:

- the strata displacement in a footwall drive by means of a precise levelling traverse
- the change in stress within a 6 x 3 m pillar by means of a vibrating wire stressmeter installed in the hangingwall of the pillar
- the on-reef stope closure by means of convergence meters, and
- the development of fracturing in a pillar by means of borehole petroscope observations.

The results obtained from the *in-situ* measurements were analysed using the computer program MINSIM[1] in an attempt to describe the strata behaviour and the stress-strain characteristics of the support pillars.

Description of the site

The experiments were carried out at approximately 930 m below surface at 14 Level, No. 10 shaft, Merensky Reef, Wildebeestfontein North Mine, Impala Platinum (Ltd). A schematic plan of the experimental site is given in Figure 1. The reef dips about 12 degrees towards the east and the stoping width averages about 1 m.

In Figure 1, the small in-panel pillars are shown only in the relevant section of the plan used for MINSIM modelling. The larger white inlying blocks represent unmined ground due to potholes, dykes, and faults.

The 14 South Drive position, where the precise levelling traverse was established, is indicated by a series of benchmark numbers from 1 to 19 and marked with the symbol *, and the site used for on-reef measurements lies above the benchmarks 5 to 8 in the block marked CW4.

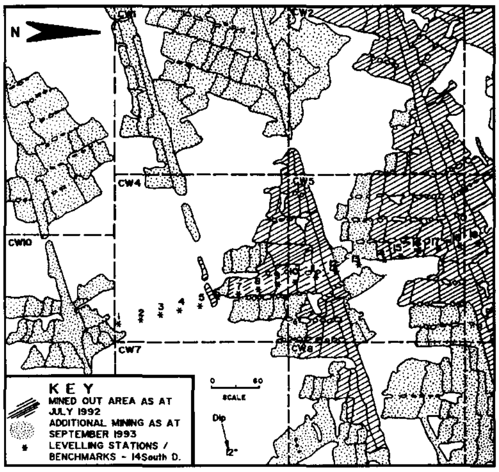

Figure 1—Plan of the experimental area at No. 10 shaft, Wildebeestfontein North Mine

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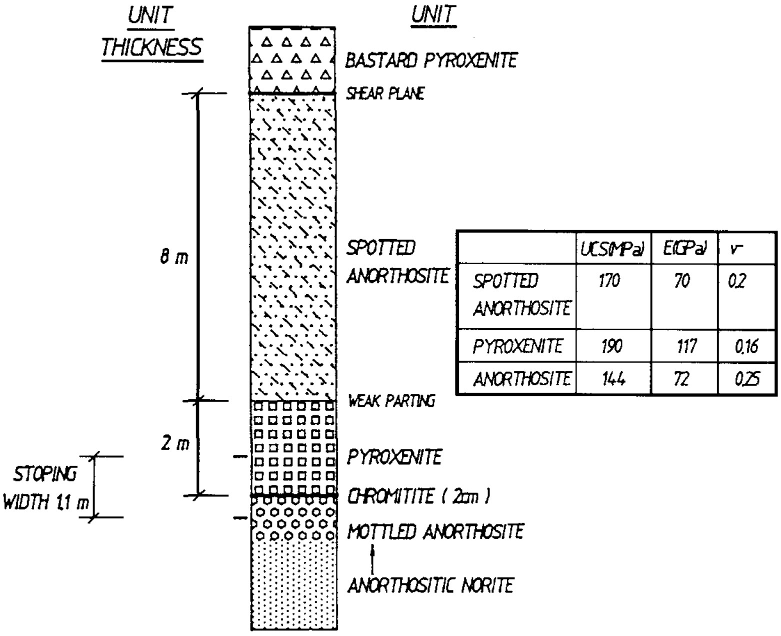
that a 6 x 3 x 1 m pillar yields without significant load shedding at peak stress levels of approximately 208 MPa. The closure measurements confirmed that the mechanism of yielding is mainly that of pillars punching into the foundations. Slight to moderate sidewall fracturing and slabbing might be contributing to yielding, but to a much lesser degree than the former mechanism, as the petroscope observation revealed the existence of an intact region beyond 0,6 m from the pillar sides.

A typical geological succession encountered at the site is given in Figure 2, together with the engineering properties of the main rock types. The mined width along the Merensky Reef comprises 70 cm of pyroxenite and 30 cm of mottled anorthosite, separated by a 1 to 2 cm band of chromitite. A weak parting plane exists approximately 2 m above the reef between the pyroxenite and a further layer of spotted anorthosite. The majority of stope hangingwall problems are related to this weak plane. At approximately 10 m above the Merensky Reef there exists a porphyritic pyroxenite layer, commonly known as the 'Bastard Merensky Reef'. The contact of this unit with the spotted anorthosite is usually marked by a well-defined shear plane, which is known to cause stope backbreaks if no pillars are employed, and historically has been used as one of the main criteria for pillar design.

Precise levelling

The precise levelling traverse for measuring the displacements induced by the mining on the Merensky Reef was established on 14 Level South Drive No. 10 Shaft, (marked with the symbol * in Figure 1). The drive is 950 m below surface and approximately 24 m below the Merensky Reef.



	UCS(MPa)	E(GPa)	ν
SPOTTED ANORTHOSITE	170	70	0,2
PYROXENITE	190	117	0,16
ANORTHOSITE	144	72	0,25

Figure 2—The rock types encountered in Merensky Reef mining

Each hangingwall station comprised a 1,8 m re-bar terminating in a stainless steel apparatus designed specifically for the hanging of Invar staves. When suspended, the staves could freely move to reach verticality. Two 3 m Invar staves were required to carry-out the levelling traverse, one being set up as a backsight, and the other as a foresight. The staves had double sets of graduations, with interval lines on the scale being 10 mm apart. This corresponded to the 10 mm range of the optical micrometer fitted to the Wild N3 levelling instrument, which was set up mid-way (15 m) between the staves during measurements. Station No. 2 was selected to be the reference point, as the computer simulations showed that the absolute vertical displacement at this location was less than 0,5 mm, which was the smallest value for all the 19 benchmarks.

Measurements and computer simulations

Levelling traverses were carried out at regular time intervals and subsequently compared to the results of MINSIM computer simulations. The hatched area in Figure 1, indicates the extent of mining at the time of conducting the first levelling measurement in July 1992, and the dotted area represents the mining that occurred until the last levelling measurement which was carried out in September 1993. Four precise levelling measurements were considered, and the face positions for each measurement are shown by the solid black lines.

For MINSIM modelling, ten coarse windows were generated with 64 x 64 grids and gridsize of 4 m, each covering an area of 256 by 256 m. Furthermore, nine fine windows, located over the drive in coarse windows CW4, CW5 and CW6, (shown in Figure 1) provided increased resolution and accuracy. Each fine window had 64 x 64 square elements with a gridsize of 1 m, allowing the small pillars in the vicinity of the drive to be modelled with acceptable accuracy.

Results

The cumulative vertical displacements obtained from *in-situ* precise levelling measurements and the MINSIM modelling, for the period July 1992 to September 1993, are summarized in graphical form in Figure 3. Only vertical components of displacements were considered as these were much larger than the other two horizontal components. The MINSIM results in Figure 3 exclude the vertical displacements which occurred prior to the first measurement date of July 1992.

Figure 3 shows that the trends of the MINSIM data sets conform fairly well with the field data up to Station No. 15, beyond which the *in-situ* measurements give larger displacement values than the MINSIM model. This may be due to the fact that the pillars located above the survey points from 15 to 20 were in a previously mined out area and could already have been yielding, thus allowing more closure than the elastic behaviour modelled by MINSIM.

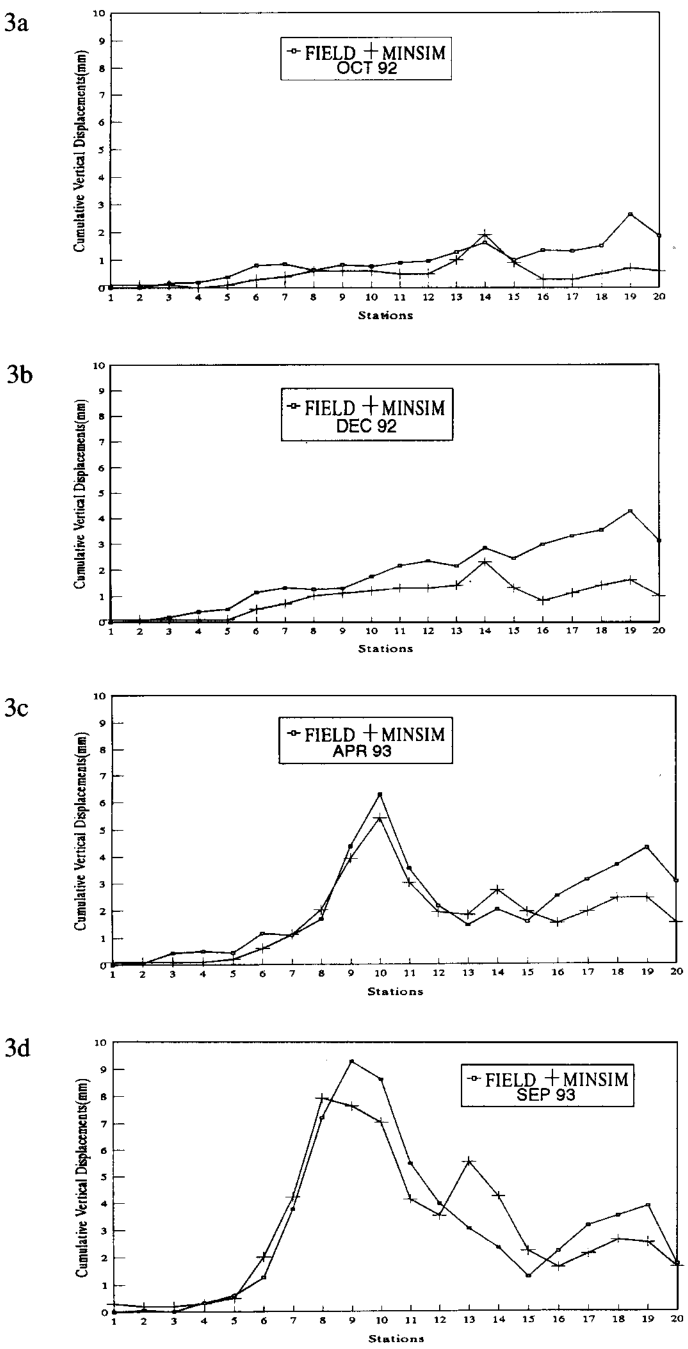


Figure 3a, b, c, and d—Cumulative vertical displacements (upwards) along the drive as calculated from MINSIM and precise levelling measurements for the period July 1992 to September 1993

In Figure 3(d), the displacements calculated using MINSIM are greater than the measured field values in the vicinity of Stations 6, 7, and 8. However, these discrepancies are marginal when compared to the large absolute (as opposed to relative) displacements induced. For example, the absolute modelled displacement of Station 8 for the September 1993 mining outline, is over 13,5 mm, while the discrepancy in cumulative relative displacements reflected in Figure 3d is only 0,7 mm. Figure 3(d) also illustrates an anomalous region between Stations 13 and 15 where the measured data indicate a downward movement as opposed to a distinct upward trend on the MINSIM curve. A possible explanation for this behaviour is that a spurious downward, inelastic movement occurred at Station 13 between the mining stages of April and September 1993.

To analyse the data further, a sensitivity analysis was carried out by reducing the secant modulus of the pillars over Stations 8 to 11, where the highest change in displacements occurred. The motivation for this procedure was based on the assumption that large displacements could be experienced by the pillars during yielding at a constant stress level, or even load shedding down to lower stresses. Interpolating from the results of MINSIM simulations, it was found that using an equivalent pillar modulus of 13,5 GPa gave the best data fit for Stations 9, 10, and 11.

In Figure 4 the field displacements are plotted which occurred between October 1992 and September 1993, and the three sets of displacements generated using MINSIM from simulations with no pillars and pillars with an elastic moduli of 68 GPa and 13,5 GPa. The pillar modulus of 13,5 GPa was selected after interpolating the displacement plots against displacements for benchmarks 9, 10, and 11. As seen, the displacements calculated using MINSIM for a 13,5 GPa modulus gives the best fit, especially at Stations 9, 10 and 11. However, the displacements at Stations 7 and 8 become larger than measured, indicating that in this region the modulus of 13,5 GPa used for the pillars is too low.

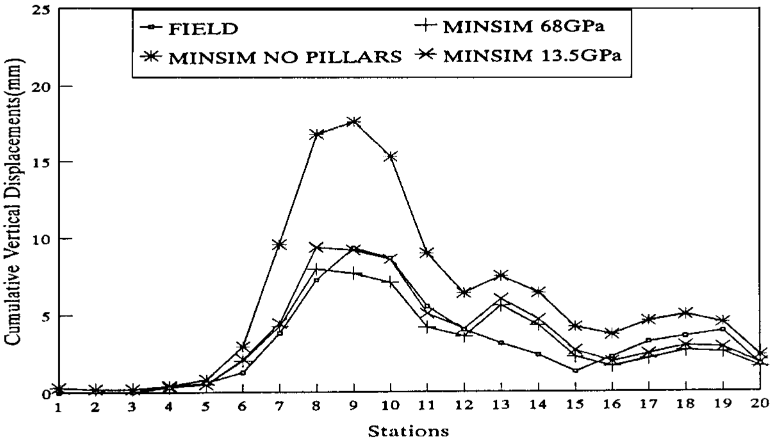


Figure 4—Cumulative vertical displacements (upwards) along the drive as calculated from precise levelling measurements and MINSIM simulations using different pillar moduli for the period July 1992 to September 1993

To minimize the difference between the field values and the displacements calculated using MINSIM at Stations 7 and 8, the modulus of the pillars above the drive was increased to 68 GPa. The final plot of the displacements is given in Figure 5. As seen, the difference between the field and MINSIM points is reduced with the higher pillar modulus above Stations 7 and 8. A possible interpretation of this behaviour is that the pillars above Stations 7 and 8 had not yet reached their elastic limits, while the others had started yielding and thereby allowed larger displacements to occur. Further modelling studies would be required to fully substantiate this hypothesis.

Nevertheless, comparing the 'no pillar' displacement curve to the other curves in Figure 4, it can be concluded that the pillars were strongly resisting the strata displacements. The changes in the degree of resistance suggest that while some of the pillars were yielding or shedding load, others had not reached their elastic limits.

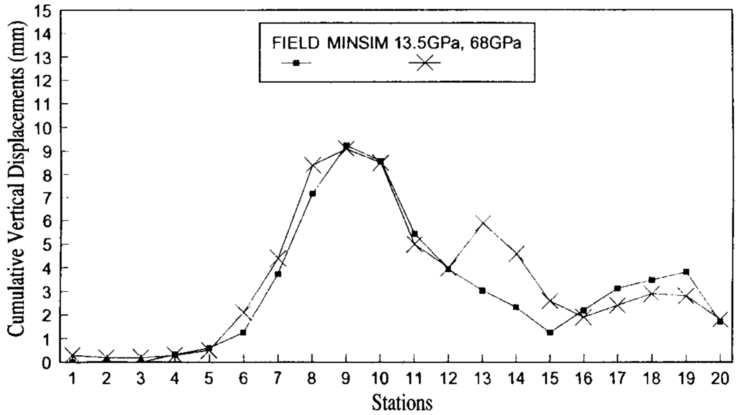


Figure 5—Cumulative vertical displacements (upwards) along the drive as calculated from precise levelling measurements, and MINSIM simulations using a modulus of 68 GPa for the two pillars located above Stations 7 and 8 and a modulus of 13,5 MPa for the rest of the pillars in the layout

On-reef stress and convergence measurements and computer simulations

Convergence measurements

Convergence measurements were carried out at positions approximately above Stations 7 and 8 at the reef level during the period May 1992 to September 1993. The location of the convergence stations are marked C1 to C4 and C21 and C22 in Figure 6. A modelling of the elasticity of the layout using MINSIM was carried out for comparison purposes.

The cumulative closure results are plotted in Figure 7. This figure shows that the maximum closure was measured at convergence meters C1 and C21, which were located within the gully siding about 0,5 m away from the Pillars P1 and P2, respectively. The large magnitudes of displacements in these stations are a result of footwall heave observed in the vicinity of the pillars. The MINSIM modelling of the layout gave convergence values in the order of 7 to 9 mm and these compare well to those measured at the locations C2, C3, C4, and C22. The implication is that the measured stope convergences, except at Stations C1 and C21, which were strongly affected by footwall heave, were due only to elastic movements of the strata.

Pillar stress measurements

A vibrating wire stressmeter was installed in the hangingwall of Pillar P1 in Figure 6, which was cut to form a 3,2 x 5,5 m pillar. The stressmeter was installed approximately 1,5 m into a +5° Ex borehole at the corner formed by thehangingwall and the siding in the abutment prior to formation of the pillar in May 1993, (see inset in Figure 6).

The stress changes measured at P1 are plotted against the closures measured at C3 in Figure 8. The closures measured in the stope are expected to be somewhat greater than the true vertical displacements experienced by the pillar and, therefore, the plot in Figure 8 is not necessarily the actual stress-displacement behaviour of the Pillar P1. Nevertheless, it can be used to trace the loading history of this pillar. It can be seen that the rate of change of stress is small, up to a closure value of 2 mm, which is probably as a result of the 'bedding in' of the stressmeter. From this point, the stress increases with increased mining up to a peak stress value of 95 MPa. This is followed by a drop in stress of approximately 6 MPa. Thereafter, the stress increases at a much reduced rate to the final value of about 97 MPa.

Acknowledgements

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References

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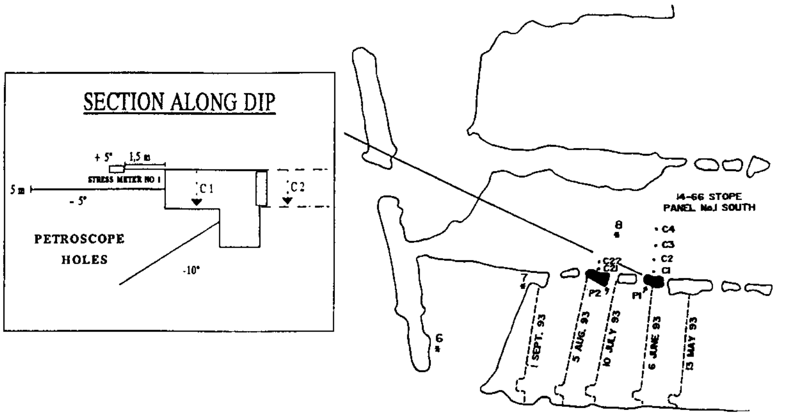

Figure 6—The location of the on-reef experimental sites, corresponding to the bottom right hand corner of the window marked CW4 in Figure 1

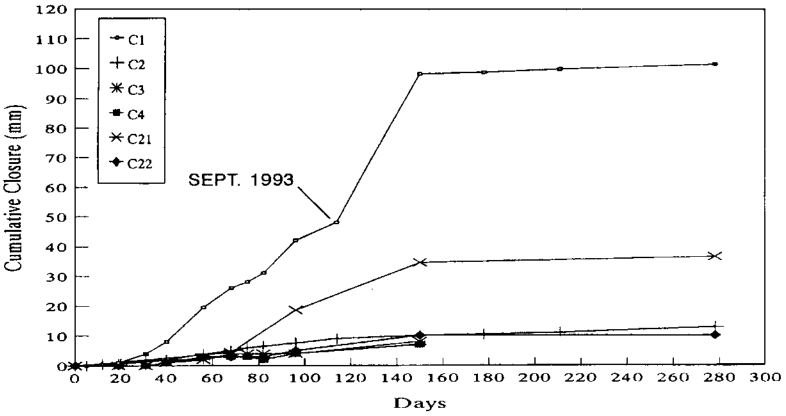

Figure 7—Cumulative closure measured in the stope for the period May 1993 to February 1994

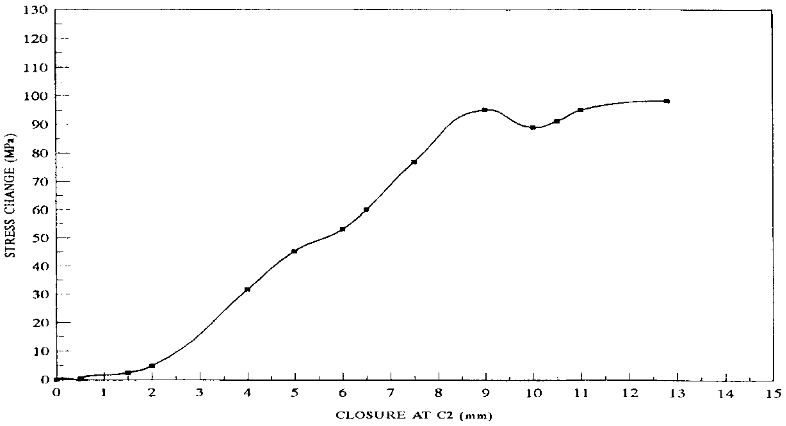

Figure 8—The stress changes measured at Pillar P1 against the closure measured at C3 (see Figure 3)

MINSIM simulations of the geometry at the time of the stress meter installation showed that the abutment stresses at the pillar location were in the order of 111 MPa. In addition, by interpreting the results of the precise levelling measurements, the modulus of the Pillar P1 was estimated to be 68 GPa. Taking 111 MPa as the initial stress level and adjusting the displacements measured at the closure meter (location C3) to give a pillar modulus of 68 GPa, the pillar behaviour given in Figure 8 is re-plotted in Figure 9. This figure shows that the pillar stress increases almost steadily with increasing pillar compression to a peak stress level of about 208 MPa, at which level the pillar starts 'yielding'. It is interesting to note that the onset of yielding corresponds to the time of large closure occurring at the convergence station C1 which was due to floor-heave next to Pillar P1. The validity of the pillar behaviour beyond the peak stress point, however, could not be verified by the results from the precise levelling measurements as no data were available after September 1993. It should also be noted that the peak-stress of 208 MPa does not agree exactly with the average pillar stress value of 247 MPa which was obtained from the MINSIM simulations. This could be attributed to an overestimation of the average pillar stress in modelling small pillar layouts using the MINSIM program[2].

A simple calculation shows that the support resistance required to stabilize the hangingwall up to the Bastard Merensky Reef is in the order of 0,3 MPa which translates to a pillar strength of 6 MPa. This is far smaller than that provided by the 6 x 3 x 1 m pillars, even after allowing a large margin of error for the estimated value of 208 MPa for the elastic limit of the pillar.

Petroscope observations

The degree of fracturing in Pillar P1 was recorded using a petroscope in the two Bx boreholes drilled at -5° in the centre of the pillar and at -10° into the footwall of the pillar, (see inset in Figure 6). The observations made are illustrated in Figure 10. There is an important implication that the fractures recorded during the initial observations did not migrate further into the pillar, although opening up of these fractures was observed as the pillar stress increased as a result of the advancing bottom panel. 'Dog-earing' commenced on the sides of the boreholes almost immediately at the end of the fracture zone in the pillar. Also observed was that the 'dog-earing' started at about 130 MPa (Figure 9), and its orientation inferred that the principal stress was normal to the reef plane. Otherwise, the centre of the pillar was observed to remain intact.

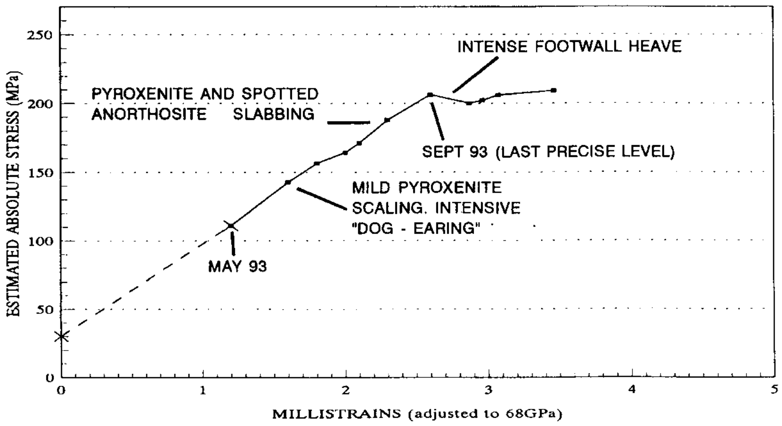

Figure 9—The adjusted stress-strain curve for Pillar P1 (see Figure 6) as estimated from field measurements and the MINSIM simulations

Conclusions

The off-reef displacements measured during the early stages conform to the trends obtained from elastic modelling using MINSIM, implying that the surrounding rockmass behaves in an elastic manner and has an elastic modulus of about 68 GPa.

The later stages of the precise levelling measurements gave better fits with the MINSIM results only after reducing the modulus of some of the pillars, indicating the possibility of these pillars 'punching' into their foundations, as discussed below.

Analysis of the *in-situ* data showed that the stress on a 6 x 3 m pillar increased with increasing mining up to a level of about 208 MPa. Further mining resulted in punching of the pillar into the footwall and the stress remained at approximately the same level. The maximum deviation was approximately 6 MPa. With this behaviour, the pillar system can be defined as 'yielding'.

Indications are that the support resistance required for the stability of the hangingwall up to the Bastard Merensky parting is well within the yielding limit of the pillar system employed.

The findings with regard to absolute values of pillar stress and strength depend on the accuracy of MINSIM modelling, which is known to overestimate the elastic stresses on small pillars slightly.

Further measurements using existing instruments and additional computer simulations, preferably using an improved version of MINSIM for more accurate estimations of pillar stresses, should provide more precise insights into pillar and rockmass behaviour at the site. ◆

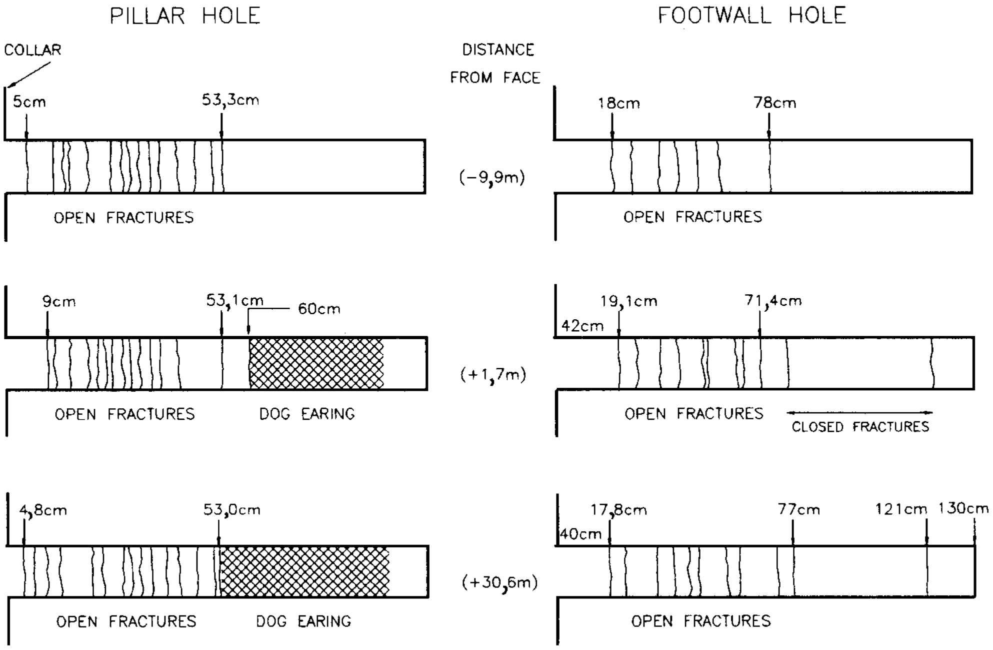

Figure 10—Results of the petroscope observations carried out in the two holes drilled into Pillar P1 (see Figure 6)