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A Trial Evaluation of Rock Core DCDA Absolute Shear Stress Measurement for Routine Quantitative Mining Hazard Assessment in Deep Underground High Stress Mines*

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It is difficult to implement routine mine-wide programs to measure absolute stress in deep and over-stressed mines because the drilled holes and cores are often damaged during and immediately following the drilling. We evaluated the use of the Diametrical Core Deformation Analysis (DCDA) method, developed by Funato and Ito, to overcome this problem. This non-destructive method can evaluate the absolute shear stresses and measurement errors in the planes orthogonal to the core axes by precisely measuring the ellipticity of the core section orthogonal to the borehole axis. The five readings required to evaluate a single core take only about ten minutes to make. The measurement system is compact enough for a single regular courier parcel or can be checked-in as luggage on a flight. Absolute shear stresses were determined for thirty-five core specimens from fourteen holes drilled in a range of directions in the highly stressed rock mass surrounding a deep South African gold mine. Using the DCDA method we were able to determine the absolute 3D shear stress field averaged over an area of interest. It was consistent with the 3D stress field measured *in-situ* with an overcoring method, with the maximum principal stress larger than 100 MPa, with a root mean square of residuals of several MPa. Interestingly, the results represent relaxation in shear stress near the fault intersected by the boreholes. The DCDA measurements require a core diameter larger than approximately 40 mm, and a core that is longer than approximately 10 cm. The method assumes that there is no significant inelastic deformation and that the rock is isotropic. [doi:10.2320/matertrans.MT-Z2024004]

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1. Introduction

A semi-critically-stressed brittle rock mass may fail violently if mining activities or the passage of a seismic wave perturbs stress. So, we need to know how critical is the state of absolute stress to quantify seismic hazard for the rock mass.

So-called "stress tensor inversion" is often carried out in seismology in areas with natural or anthropogenic seismicity as reviewed in *e.g.*, Zoback and Kohli (2019) [1]. If one monitors earthquakes, one can determine the direction of the principal stresses and the temporal change in shear stress (seismic stress drop in a 3D tensor form) through the inversion. Some methods are proposed to constrain the values $(S1 - S2)/(S1 - S3)$ calculated from the three principal stresses S1, S2, and S3 since, *e.g.*, Michael (1984) [2]. If a sufficient number of earthquakes occur over a wide area, one can map the stress drop tensor over the area with seismicity. However, those are not absolute shear stress but temporal change in shear stress. Nor do they tell us anything about stress with no seismic activity. In general, seismic activity is low prior to mining, so seismic waveform analysis is not always helpful for hazard assessment prior to mining.

We investigate how the Diametrical Core Deformation Analysis (DCDA; developed by A. Funato and T. Ito [3]; see the details in Section 2) can contribute to the swift routine mine-wide quantitative assessment of rock seismic hazards in mines around the world.

The core samples and information on drilling and mining used in this study were obtained through the project "Observational studies to mitigate seismic risks in mines" (2010–2015) [4–6]. This project was conducted under the auspices of the Science and Technology Research Partnership for Sustainable Development (SATREPS) program, jointly sponsored by the Japan Science and Technology Agency (JST) and the Japan International Cooperation Agency (JICA). This initiative was implemented under a MoU signed between the South African government and JICA. The project aims to contribute to the United Nations Sustainable Development Goals (UN SDGs) in general, and specifically to safety and sustainable development in gold mining, which is a key industry in South Africa. Ten Japanese and three

*This Paper was Originally Published in Japanese in J. Soc. Mater. Sci., Japan **71** (2022) 259–265. All contexts are identical to those published in Japanese, except for (1) the use of "absolute shear stress" with additional explanation instead of "absolute differential stress", which has the same physical meaning, to avoid the inconsistency of "absolute differential"; (2) the use of Fig. 29 of Tucker *et al.* instead of Fig. 1 of our paper to better illustrate drilling in mines; and (3) the citation of Funato (2021), the co-author's latest report, in a summary section. Acknowledgement is added.

South African research institutes collaborated in the project, which was conducted at six gold mines operated by the three major South African gold mining companies.

Most of the world's 10 deepest mines are the gold mines in South Africa [7], which accounted for two-thirds of the world's gold production in 1970. In South Africa, the typical maximum mining depth is about ten thousand feet (about 3–4 km below the surface). In order to maintain the sustainable development of a South African core industry, the DeepMine and FutureMine Collaborative Research Programmes (1998–2003) reviewed the various technologies involved in mining at great depths, investigated potential areas for improvement [8]. As part of the DeepMine research programme, three stress measurement methods used in the country at that time were compared, *viz.* CSIRO Hollow Inclusion (HI) Cell, CSIR Triaxial Cell, Door Stopper. They all involve over-coring, necessitating a hole with a diameter of about 100 mm [9]. Tests were carried out at a depth of 3352 m. Prior to this, the deepest published measurements had been at depths of about 2600 m, some 700 m shallower. It had been found that in situations where the stress level was high and the orientation of the borehole for the measurement was poor, the borehole would break out or close immediately after drilling, making the measurement extremely difficult. A total of 10 strain cells were required to obtain a single reliable measurement result, and *in-situ* stress measurement was considered to be not worth the cost and effort. Since then, gold mining has continued at great depths and in highly stressed rock mass with few *in-situ* measurements available [10, 11].

The Compact Conical-ended Borehole Overcoring (CCBO) technique is a stress-relief method developed by K. Sugawara and Y. Obara [11]. It can be used in smaller diameter pilot holes, which are faster to drill and are more flexible with regard to drilling direction. Furthermore, the measurements can be obtained in a shorter overcoring distance; and the method also allows for repeated measurements in the same hole over shorter periods of time. The smaller hole size reduces the risk of hole and core fracture during drilling due to the scale dependency of rock strength. In South African mines, small-diameter holes (several cm in diameter; *ca.* 10 m to several 100 m in length) are routinely drilled for exploration and preliminary investigation of the presence of hazardous water and gas, as seen in Fig. 29 of Tucker *et al.* [12]. Since these hole diameters are smaller than those used by K. Sugawara and Y. Obara, we adapted and transferred the CCBO technology to South African conditions within the framework of the JST-JICA SATREPS project [13], making *in-situ* 3D absolute stress measurement in deep and highly stressed rock masses possible and enabling mine-wide computer stress models to be calibrated [14, 15]. However, even with the CCBO method, obtaining *in-situ* measurements from a single underground site requires, at a minimum, several shifts (typically a week of work) and many steps of underground on-site work.

The host rock of the gold mine is a metamorphosed sedimentary rock consisting mainly of siliceous rock 2.8 billion years old, which is relatively isotropic and homogeneous before mining. However, as mining progresses and stress concentration and fracturing increase, the spatial heterogeneity of physical properties and stress disturbance cannot be ignored. It has been reported that the assumption that the magnitude of principal stress is directly proportional to depth does not hold for geologically old, hard and dense rock masses such as the Canadian shields [16]. This may also apply to similar geological conditions in South Africa. When the hypocenter of an earthquake is close, the change in stress with time is also large (*e.g.*, K. Sakaguchi *et al.* [17]). Therefore, in deep underground mines, where the risk of induced earthquakes is significant and must be reduced, it is important to obtain stress information at multiple points. A method to obtain such information quickly has been urgently needed.

In the South African gold mines, many drilling cores are geologically logged at surface core yards and routinely aggregated into the mine's CAD database with information on their location in the hole. It would be efficient if this large number of well-organized cores could be used for stress measurements. The gold mining industry has been the backbone of the South African economy, but most of the remaining gold resources are found highly stressed remnant pillars or at great depths. Efforts to make mining safer, more efficient, and more sustainable are important. The factors motivated the development of other stress measurements methods.

2. Diametrical Core Deformation Analysis (DCDA) [3]

2.1 Principle of the DCDA method

If the rock mass is assumed to be an isotropic homogeneous elastic body, and the maximum principal stress in the plane orthogonal to the borehole axis is S_{Hmax} and the minimum principal stress is S_{hmin}, when the core is cut out of the rock mass, the cross section orthogonal to the core axis becomes an ellipse due to elastic deformation, as shown in Fig. 1. If the diameter of the core at the moment of cutting is d_0, and the maximum and minimum diameters of the core after deformation by stress release are $d_{\max}$ and $d_{\min}$, respectively, the relationship becomes as follows [3]

$$S_{\mathrm{Hmax}} - S_{\mathrm{hmin}} = (d_{\max} - d_{\min})/d_0 \cdot E/(1+\nu) \approx (d_{\max} - d_{\min})/d_{\min} \cdot E/(1+\nu),$$

where E and ν are Young's modulus and Poisson's ratio, respectively.

Since the difference between d_0 and $d_{\min}$ is on the order of $1/1000$th or less of d_0, a good approximation can be obtained by using $d_{\min}$ instead of d_0 in the above equation.

2.2 A portable non-destructive measurement device [3]

When detecting a shear stress of about 1 MPa in a 40 mm

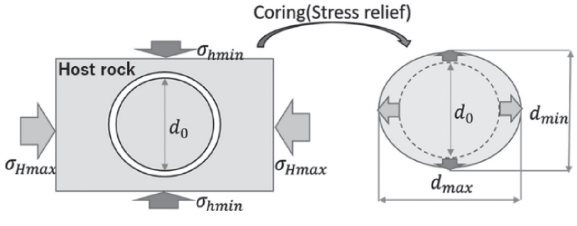

Fig. 1 The principle of elastic deformation during coring [1].

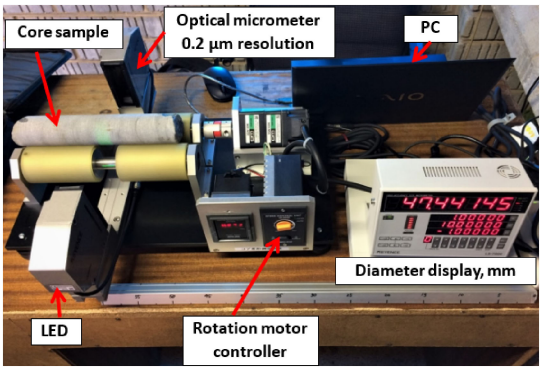

Fig. 2 The DCDA measurement system (Funato's 2017 model), compact enough for a single regular courier parcel or a piece of check-in luggage for an international flight.

diameter core of standard quartzite (*E ca.* 70 GPa; *ν ca.* 0.20) in the Witwatersrand gold mining district in South Africa, the diameter difference ($d_{max} - d_{min}$) is about 0.35 μm. Funato and Ito have developed a system to detect this difference. The core is placed on a rotating roller stand and rotated. Figure 2 shows the 2017 model of the system, which was downsized based on the experience of measurements in South Africa and other countries in 2016. The size and total weight of the case are within the range of the standard size for domestic courier services and one piece of checked baggage for international passenger flights. It does not need a laboratory but can be operated on an office desk. It can measure the prior shear stress of a single core sample in about 10 minutes in a nondestructive manner.

3. The Cores and Results of Stress Measurements

3.1 Highly-stressed shaft pillar at a *ca.* 1 km depth

In 2010, the microfracture observation group of the SATREPS project (led by Masao Nakatani) deployed a comprehensive observation network including acoustic emission sensors, and succeeded in observing in detail the formation and growth of microfractures in the rock mass caused by mining [17, 18]. The observation network was installed in a 200–250 m remnant pillar that surrounds the vertical shaft barrel at a depth of approximately 1 km (Fig. 3(b)). The purple line in Fig. 3(b) indicates the intersection of a fault zone (a normal fault with a maximum throw of approximately 30 m) and the Elsberg B gold reef. Thirty-two sensor holes were drilled before the start of gold mining in the northern part of the shaft pillar, targeting one of these faults (translucent green plate in Fig. 3; striking approximately north-south and dipping approximately 50° west). The thin lines and circles in Fig. 3(b), (c), (d) are 14 of the 32 sensor holes and the in-hole locations of the cores selected for stress measurements (Table 1 for the details of each hole), respectively.

The host rock of the borehole is a 2.8 billion-year-old quartzite (EC Formation; without clay). The gold-bearing siliceous conglomerate (Gold reef EB Formation in Fig. 3(a))

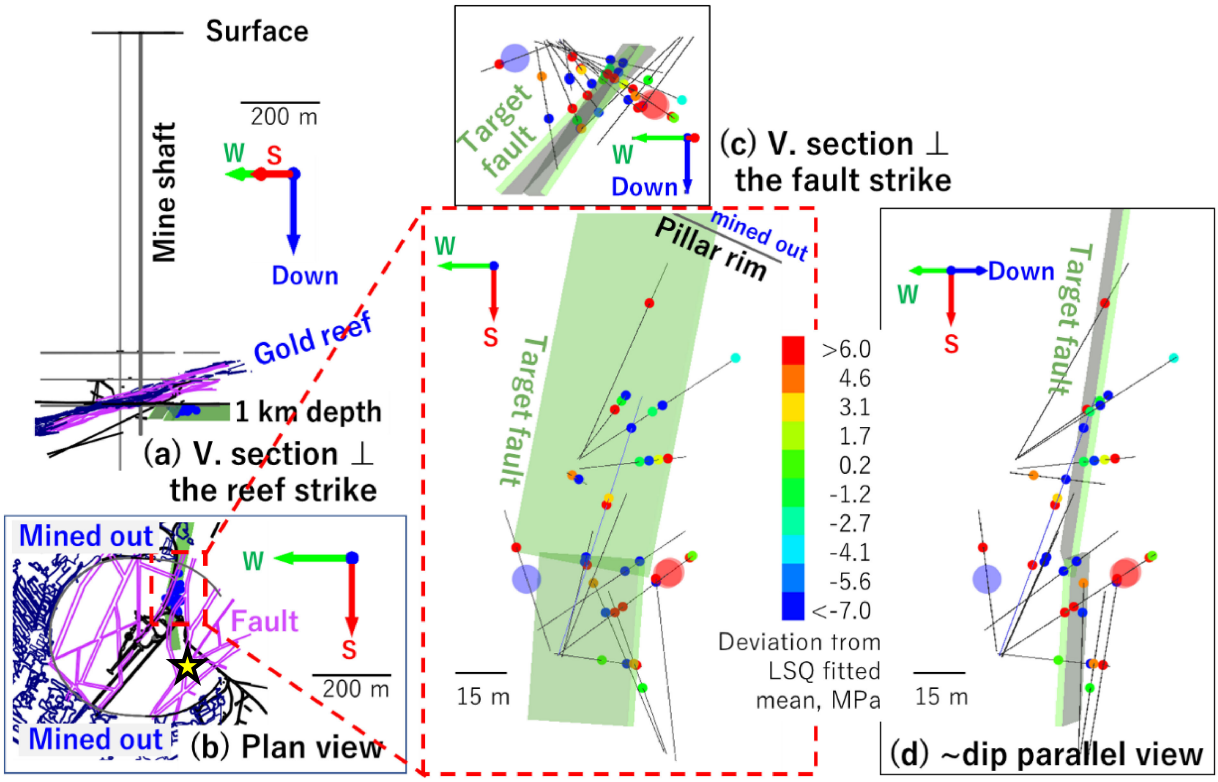

Fig. 3 The configuration of the boreholes (black thin lines in (b), (c) and (d)) and the locations (dots) where the core samples are selected for this DCDA. The mine's infrastructures and relevant information are also shown. See the details of the boreholes in Table 1. The locations highlighted with larger circles correspond to the data also highlighted in Figs. 8(a) and 9(a). The color for each dot represents the magnitude of deviation, MPa, with respect to the calculated value from the mean 3D differential stress field determined by the least-square-method (LSQ). A yellow star represents the location where an overcoring stress measurement was carried out (see Table 2 and Fig. 7 yellow symbols).

Table 1 Borehole details. *: degrees downwards, **: degrees clockwise from north. DCDA: the number of cores DCDA measured. Accepted: the number of cores accepted for the integrated analysis.

Hole name	Plunge*	Trend**	Length, m	DCDA	Accepted
AE0207	39.1	98.2	31.5	5	3
AE1205	47.5	37.2	34.5	3	3
AE1206	79.6	120.9	35.1	3	2
AExc03	21.0	353.8	55.8	2	2
PL0201	10.0	56.0	50.7	3	2
PL0202	10.2	342.0	42.2	3	2
PL1202	28.0	83.6	38.8	5	4
PL1203	17.7	57.0	54.8	6	3
RF0208	24.6	53.6	52.4	7	6
RF0211	10.5	17.8	77.4	4	4
RF1207	18.0	24.0	63.5	1	1
TR0209	21.5	13.6	39.0	2	2
TRxC01	26.7	337.5	58.0	3	2
TRxC02	31.8	340.5	57.0	2	2
			Total	49	38

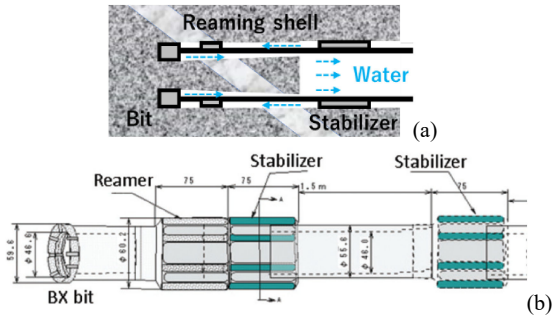

Fig. 4 The schematics representing the drilling with reverse circulation (a) and a recommended string sequence (b) [13]. Dashed arrows represent water that flows back inside the drilling rods to push out drilled cores. For the measurement, we select the core without cracks, veins as shown in (a), or lithological boundaries.

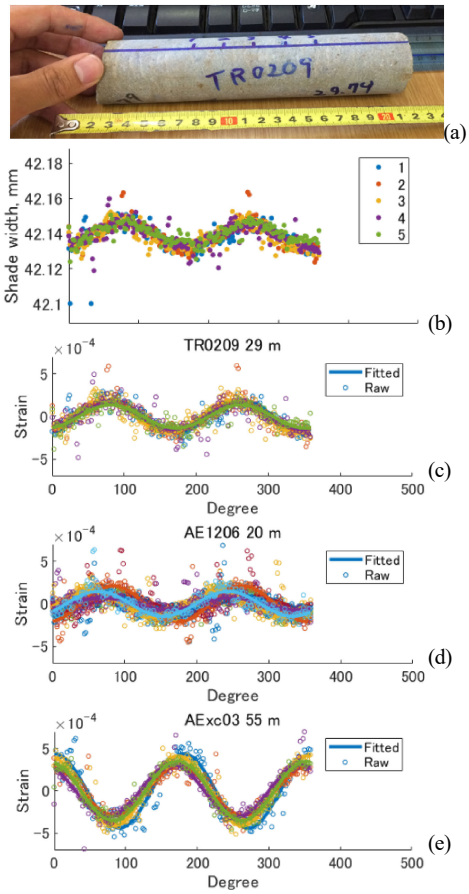

Fig. 5 Good examples [22]. The core sample TR0209 at 29 m: (a) a photo, (b): raw data, (c) strain and fitted sinusoidal curves. (d) and (e): the other good examples for comparison.

dips southward at about 20°, and clay-bearing siliceous rocks flank the top and bottom of the reef. The uniaxial compressive strength of the EC siliceous rocks was about 200 MPa (standard deviation about 30 MPa) and the corresponding elastic strain was 2000–3000 μstrain [20, 21].

3.2 The drilling and core handling necessary to get the cores for reliable measurement

The smoothness of the drilling and the handling of the core after drilling are important because the quality of the measurement results depends largely on the degree of smoothness of the cylindrical side-surface of the cores. In this study, the core was drilled using the method of diamond-drilling with reverse circulation of water. The core cut out of the rock mass is pushed up to the hole collar by water through the drilling rod, and the core is not damaged before it is recovered (Fig. 4). This method is cost-effective for a small pneumatic drilling rig for AX or BX (~48 and ~60 mm diameter) drilling with drilling ranges < several tens of meters. So, it has been widely used for routine geology exploration in South African gold mines over decades.

In the case of drilling-water circulation from inside the rod, a double tube is required at least to prevent the core from being damaged by the disturbance inside the rod.

In all cases, reaming shells and stabilizers must be installed to prevent the drilling rods from rattling or deflecting in the hole. Care must also be taken to prevent damage to the surface of the core during core removal.

3.3 Selection of a suitable core for measurement

In 2016, six years after drilling, Akimasa Ishida, Siyanda Mngadi, Akio Funato, and Yasuo Yabe selected 49 cores (Fig. 5(a) is an example) from the cores in storage at the Council for Scientific and Industrial Research (CSIR) in South Africa that had little discing or drilling damage. The condition of the core surface was determined by visual examination and by finger touch. As shown in Fig. 6, cores containing veins were excluded from the measurement [22]. Finally, 38 cores were used for the evaluation (Table 1).

3.4 Measurement of each core

A minimum of five measurements (2 cm spacing) were taken for each core, and d_{max} and d_{min} were determined by fitting a sinusoidal curve with the MATLAB® function "fitlm" (linear regression; robust option) in the MATLAB® machine learning toolbox. A good example and a bad example (due to the presence of a quartz vein) are shown in Fig. 5 and Fig. 6, respectively. If the amplitude exceeds a few tens of μ strains or the differential stress exceeds a few MPa, it can be detected (Fig. 5(c), (d), (e)) with an acceptable resolution.

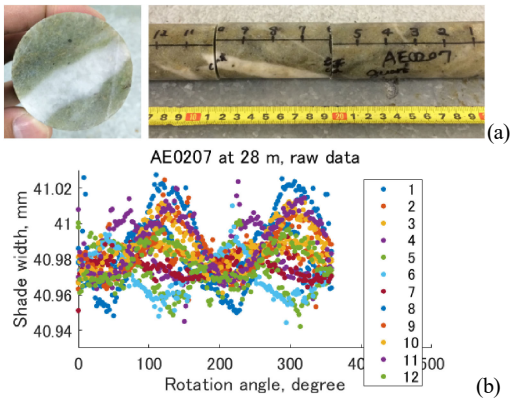

Fig. 6 A bad example [22]. The scale of the vertical axis is the same as Fig. 5(a).

3.5 Constraining the average 3D deviatoric stress field over a ~100 m extent of interest

Figure 5(d) shows an example obtained at a distance of 20 m from the collar in borehole AE1206, where 20 cross sections were measured. As borehole AE1206 (Table 1) plunges almost vertically downward, Fig. 5(d) suggests significant shear stress in the horizontal plane, or in horizontal principal stress. Consistent results were obtained elsewhere in borehole AE1206 (not shown in the figure). The boreholes TR0209 and AExc03 plunge about 21° degrees downward, while their azimuths differ by ~20° (Table 1); the measured differential strains (Fig. 5(a)–(c) and Fig. 5(e)) differ significantly. This suggests a significant difference in the principal stress values in the horizontal plane.

From the above, we can expect to constrain the average three-dimensional (3-D) deviatoric stress field (the average stress subtracted from the diagonal term of the 3-D stress tensor) in the entire analysis area. If we assume a 3-D deviatoric stress field uniformly distributed over the entire analysis area, we can calculate the maximum differential stress in the plane orthogonal to each borehole axis, taking into account the trend and plunge of each borehole (Table 1). We used a code developed by Higashi [23] that employs the MATLAB® function "lsqnonlin" in the MATLAB® optimization toolbox to find the optimal 3-D deviatoric stress field to minimize difference between the observed and calculated differential stress for each borehole. The rock properties used were those described in Section 3.1.

Only a 3-D deviatoric stress tensor with 5 independent components (not a 3D absolute full stress tensor with 6 independent components) can be determined from the DCDA measured data. The values of $\sigma_1 - \sigma_3$ and $\sigma_2 - \sigma_3$ in Table 2 and the directions of the three principal stresses shown in Fig. 7 highlighted in gray are those determined by the DCDA measured data. In order to obtain the values of σ_1, σ_2, and σ_3 in Table 2, we assumed and fixed the value of the vertical normal stress component equals to 90 MPa (about three times the stress of 27 MPa of the overburden pressure).

Figure 8(a) plots the determined magnitude of $\sigma_{1p} - \sigma_{2p}$, where σ_{1p} and σ_{2p} are the maximum and minimum principal stresses in the plane orthogonal to the borehole axis, versus the Least-Square-fitted (LSQ fitted) magnitude of $\sigma_{1p} - \sigma_{2p}$ calculated by assuming the stress field (WO shown in gray in Table 2 and Fig. 7) is uniformly distributed over the volume of interest. The residuals are not symmetrical in the histogram (Fig. 9(a)), and some of them are nearly three times the standard deviation of 8.5 MPa. A dot with a blue circle in Fig. 8(a) shows that the deviation below the regression line is largest, which is just below the tunnel, where the stresses should be low (large blue circles in Figs. 3(c), (d), 8(a), and 9(a)). We excluded the three outliers (highlighted by blue and red ellipsoids in Figs. 8(a) and 9(a)) to have the improved R^2 values (Fig. 8(b)), and to reduce the standard deviation of

Table 2 Comparison of the measured principal stress values, MPa. Pre-mining DCDA (this study) with and without outliers (WO and WoO, respectively). Overcoring: post-mining CCBO overcoring [14].

Pre-mining (This Study)	Measured stress, MPa and symbols in Fig.7 σ_1 ○	σ_2 △	σ_3 □	$\sigma_1 - \sigma_3$	$\sigma_2 - \sigma_3$
DCDA WO	124 ± 9	104 ± 10	78 ± 8	46	26
DCDA WoO	110± 7	68± 7	55± 9	55	13
Post-mining Overcoring [14]	127 ± 3	41 ± 3	36± 3	91	5

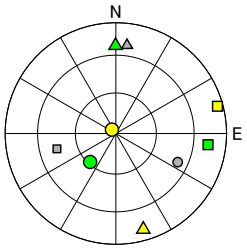

Fig. 7 A composite plot of the three results to compare the plunges and orientations of the measured principal stresses. Gray and green: pre-mining DCDA (WO and WoO, respectively; this study). Yellow: post-mining overcoring [14] at the location in Fig. 3(b). See measured values in Table 2. ○: σ_1, △: σ_2, □: σ_3.

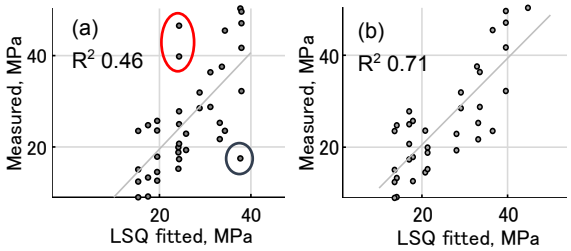

Fig. 8 A scatter plot of the measured versus the calculated stress. (a): all data with outliers; WO in Table 2 and Fig. 7. The locations for the data highlighted here are represented by larger circles in Fig. 3(c), (d). (b): without the data highlighted in (a); without outliers, WoO in Table 2 and Fig. 7.

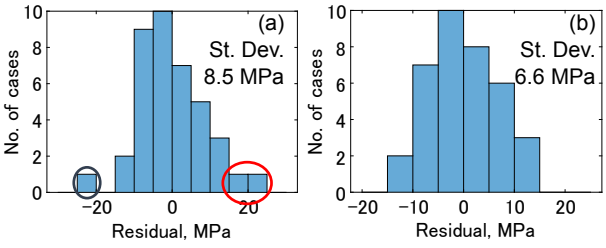

Fig. 9 (a) and (b): the histogram of the residuals with and without the data highlighted in Fig. 8(a) and 8(b), WO and WoO, respectively.

residuals and improve the symmetry in histograms of residuals (Fig. 9(b)).

Stress measurements were made using the CCBO method in the southeastern part of the shaft pillar (yellow star in Fig. 3(b)) after about a half of the pillar had been mined and the vertical stress had increased [14]. The results of the CCBO method and the three principal stress directions of the DCDA (yellow and green in Table 2 and Fig. 7, respectively) are in accord, and it is reasonable to expect that the shear stress after mining is large.

The color of each dot in Figs. 3(b), (c), and (d) indicates the magnitude of the residuals shown in Figs. 8(b) and 9(b). The darkest red and the darkest blue indicate the cases where the absolute value of the residual is close to or exceeds the standard deviation of residuals of 6.6 MPa. Interestingly, as can be seen in Fig. 3(d), the darkest blue is concentrated near the fault plane, while the darkest red appears to be distributed also near the fault plane but off the fault. If stress is easily released in the elastic body near the fault, stress can be concentrated at the periphery, so stress release and associated stress concentration may be depicted.

3.6 Rock mass inelasticity

The stress-strain curve in the determined stress range was linear [20, 21]. For other samples of the same lithology from South African gold mines, S. Abe [24] measured the change in anelastic strain relaxation (ASR) with time after unloading, and confirmed that ASR does not exceed 30% of elastic deformation. The measurement accuracy of absolute stress is reduced by the ASR. However, if the extent of the problem can be ascertained, it will be less of a practical problem.

4. Conclusion

In rock mass prone to induced seismicity, stress and rheological properties are expected to be spatially heterogeneous. However, there was no rapid method to measure stress in South African gold mines, where mining takes place over large areas and may extend for distances as great as 3 km from a single shaft.

In this study, the maximum differential stress in the plane perpendicular to the core axis was determined with an accuracy of a few MPa using the DCDA method. The DCDA method is a nondestructive method to measure the stress close to a borehole. The DCDA instrument is portable and does not require any special laboratory facility. Measurements were made on 38 unoriented cores (diameter: about 40 mm, length: more than 10 cm) obtained from 14 boreholes. An integrated analysis was attempted. It was confirmed that the least-squares solution of the average three-dimensional deviatoric stress field could be determined and that the spatial distribution of deviations (residuals) from the solution could be used to identify areas of relaxation and concentration in stress in rock mass.

In South African gold mines, exploration drilling is routinely carried out underground in various directions from various localities to determine the location, strike and dip, and displacement of the gold reefs, and to optimally plan tunnel development and mining. The more complex the geological structure, the more drilling is done. Although the core is not usually oriented, the orientation and inclination of the hole and the depth from the hole opening are surveyed, and the information on lithology and geological structure is compiled in the mine CAD geology database. Routine application of the DCDA method to measure stress relief, and hence deviatoric stress, should provide far more information to support mine design and seismic hazard assessment than has hitherto been provided by conventional stress relief methods (*e.g.* CSIRO HI or CCBO) that provide only one-off and localized information.

The remaining challenge is to evaluate the results in lithologies other than relatively homogeneous siliceous rocks. In other mines in South Africa, drilling cores have been obtained from more complex conditions such as metamorphosed mudstone, shale, lava, and altered mafic intrusive rocks [25, 26], and stress analysis is in progress [22, 27]. Based on these results, we would like to share our achievements with those involved in deep and high stress mines around the world [28] and contribute to the United Nation's Sustainable Development Goals (SDGs).

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