

Assessing the stress field for the Jwaneng underground project

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Abstract

The Debswana Diamond Company (DDC) Jwaneng Mine in Botswana, is a large open pit diamond mine extracting three kimberlite pipes. Open pit operations will cease in the early 2030s; studies are currently underway to transition to an underground operation by the time open pit mining ceases. It is anticipated that underground mining will be undertaken using a combination of sublevel caving (SLC) and other caving methods; mining will extend to a depth of ~1,000 m below surface.

The Jwaneng Mine is structurally complex with many large geological structures and a variable rock mass, with strengths ranging from weak kimberlites (25 MPa) to very competent dolomites (>250 MPa).

Understanding the in situ stress regime is an important input for underground mine design and has a significant impact on designs analyses including numerical modelling. The magnitudes, ratios and directions of the principal stresses influence the choice of mining method, excavation stability, stand-off distances, extraction sequence etc. Various evaluations have been undertaken and this includes stress measurements using the Sigra in situ stress test (IST) and the deformation rate analysis (DRA) methods. In addition, borehole ovality analysis using televiewer data has been undertaken on ~100 boreholes to assess the orientation of the maximum horizontal stress.

In addition to these measurements, the literature has been reviewed and independent reviews of all work have been undertaken. The outcomes from the various methods do not always agree and the interpretation of the stress field in a complex geological environment is not straightforward and has associated uncertainties. The interpretation of the data is an iterative process with different approaches applied with the aim of developing reasonable stress field inputs and sensitivities for design analysis. The process followed and the outcomes will be discussed in this paper.

Keywords: *in situ stress field, stress magnitude, Sigra in situ stress test, deformation rate analysis, ovality analysis*

1 Introduction

The Debswana Diamond Company (DDC) Jwaneng Mine in Botswana, is a large open pit diamond mine extracting three kimberlite pipes. Open pit operations will cease in the early 2030s; studies are currently underway to transition to an underground mining operation by the time open pit mining ceases. It is anticipated that underground mining will be undertaken using a combination of sublevel caving (SLC) and other caving methods. Mining will extend to a depth of ~1,000 m below surface and will include excavations within very competent country rock and weak kimberlite rock.

Understanding the in situ stress field is an important component and input into the design of an underground mine employing massive mining methods. Preliminary numerical modelling included sensitivity analysis for different stress fields, and this shows significant differences in outcomes, reinforcing the need to gain a better understanding of the in situ stress field.

2 Jwaneng mine setting

2.1 Location

Jwaneng Mine is situated approximately 160 km southwest of the capital city of Gaborone in the eastern part of the Kalahari Desert (Figure 1). It was discovered in the Naledi Valley, southern Botswana, in 1972. In July 1982, the mine went into production and became fully operational in August of the same year. Figure 1 shows the geographical location of Jwaneng Mine in southern Botswana (Gabanakgosi et al. 2018).



Figure 1 Location of Jwaneng Mine in southern Botswana

The mine operates a split shell pushback approach; Cut 7 and Cut 8 are currently being mined and stripping for Cut 9 has commenced. Jwaneng Mine is currently undergoing a critical transition in its life with the current Cut 8 mining expected to take the pit from the current depth of about 444 m below surface (726 m above mean sea level (AMSL)) followed by Cut 9 down to a depth of about 624 m below surface (546 m AMSL). The major axis of the pit has a general north-northeast–south-southwest orientation, with the waste dumps located to the west of the pit and the process plant to the east (Gabanakgosi et al. 2018).

2.2 Geology

The Jwaneng Mine country rock stratigraphy comprises Paleoproterozoic sedimentary rocks of the Pretoria Group within the Transvaal Supergroup. The upper-most stratigraphic units are the aeolian Kalahari Sands, as well as pedogenic calcretes. These units are underlain by the Timeball Hill Formation, which comprises a complex assemblage or mixture of laminated shales, quartzitic shales, and siltstones combined into one laminated shale unit. A consistent carbonaceous shale layer marks the base of the Timeball Hill Formation (Barnett 2009). The Timeball Hill Formation is underlain by the Rooihooigte Formation which consists of medium-grained, poorly sorted, and argillaceous quartzites, which could in general be classified as greywackes to sub-greywackes, and silty mudstone. Below the Rooihooigte Formation are carbonates (dolomites) of the Malmani Subgroup which are stratigraphical correlatives of the Campbellrand Subgroup in Griqualand West (Beukes 2006). The simplified stratigraphy is shown in Table 1.

The Jwaneng Mine exploits a diamond-bearing kimberlite complex of three main pipes; these pipes have been named South (S), Centre (C) and North (N) pipes. All three pipes are associated with steep (~80°) and

relatively smooth sides. The contacts with the country rock (which is locally fractured adjacent to the kimberlite) is typically very sharp. Before the onset of mining, the upper portions of the pipes were dominated by reworked volcanoclastic sediments with shallow dipping bedding structures. This is underlain by the main pipe infill which is typically dominated by broadly massive volcanoclastic kimberlite (with bedded pyroclastic and volcanoclastic units preserved in the North Pipe).

Table 1 Jwaneng country rock stratigraphy

Stratigraphic name	Rock type	Code
Kalahari Sequence	Sand	SAND
	Calcrete	CALC
Timeball Hill Formation	Laminated shale	LS
Lower Timeball Hill Formation	Carbonaceous shale	CS
Rooihoogte Formation	Quarzitic shale	QS
	Chert pebble conglomerate – bevets	BVT
	Quarzitic shale	QS
Lower Rooihoogte Formation	Carbonaceous shale	CS2
Mlamani Subgroup	Dolomite	DM

2.3 Structural setting

The structural setting at Jwaneng Mine is complex and the structural model is regularly updated as new mapping and drillhole information becomes available. The structural geology at Jwaneng Mine is clearly dominated by northeast–southwest striking faults with a strong normal dip slip shear sense component (Figure 2). These faults are downthrown to the southeast and compartmentalise the shallow to intermediately north-west dipping strata into structural domains each with a unique rock fabric (Barnett 2009).

Creus et al. (2017) suggest that the Jwaneng Mine country rock has been subjected to at least three deformational events. The first deformation (D1) is northwest–southwest directed compression which resulted in northeast trending open folds (F1) and low-angle thrust faults that tend to dissipate into bedding.

Creus et al. (2017) further suggests that the second deformation (D2) involved the rotation of principal stress to north–south that resulted in north–south shortening leading to sinistral, oblique shearing along the pre-existing radial cleavage developed around the F1 folds coupled with development northwest trending open folds (F2).

The third deformational event (D3) is a northwest–southeast extensional deformation leading to development of normal faulting along pre-existing F1 cleavage creating a series of wedge-shaped, fault-bounded blocks. The normal faulting was coupled with rotation of blocks towards the north resulting in a high dip value on the eastern slopes daylighting into Jwaneng Mine open pit (Creus et al. 2017).

2.4 Regional stress setting

Various sources were consulted to gain a perspective of the regional stress setting; the World Stress Map (WSM), a stress review of South Africa undertaken by Stacey & Wesseloo (1998) and work by Handley (2013) into the crustal stress state (CSS) were considered in deriving the first estimates of the stress state for Jwaneng Mine. Work on stress and strain rate in South Africa by Bird et al. (2006) has also been considered. From these resources it was inferred that the maximum horizontal stress is oriented northwest–southeast.

Creus et al. (2017) inferred that the prevailing geological stress regime was extensional in a northwest–southeast direction and that Jwaneng may be at the northernmost limit or edge of the early, north directed compressional deformation event. The back-analysed most likely stress state for the fault mechanism thought responsible for the deep crustal April 2017 earthquake is also northwest–southeast extensional.

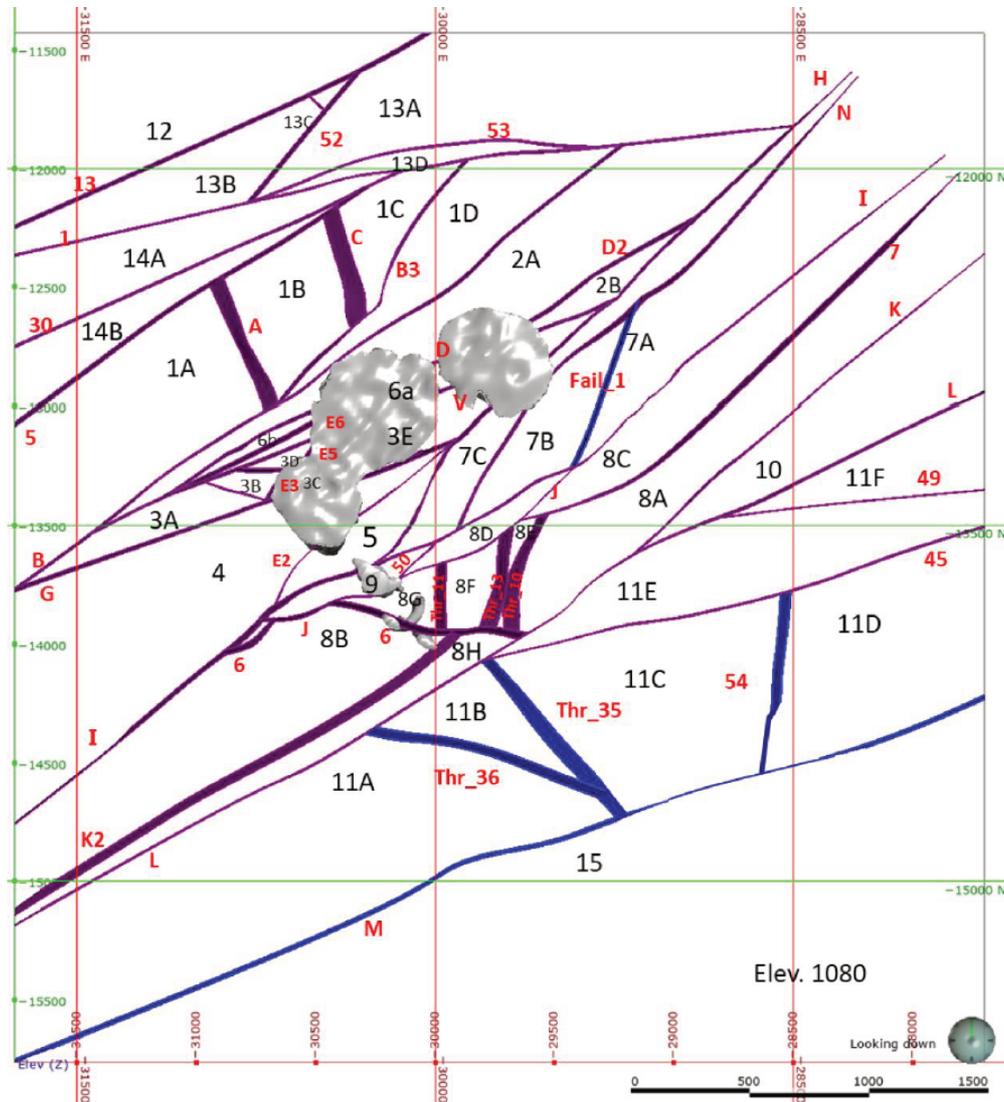


Figure 2 Large-scale faults at Jwaneng Mine (Barnett 2020)

3 Stress measurement at Jwaneng

Several methods over several campaigns have been undertaken to estimate the in situ stress field at Jwaneng Mine. These are listed below, and results are summarised in subsequent sections.

- Sigra in situ overcore (2013).
- Deformation rate analysis (2017).
- Sigra in situ overcore (2019–2020).
- Borehole ovality analysis (2020).
- Borehole ovality extended analysis (2022).

Figure 3 shows the locations of all Sigra and DRA measurements as well as selected boreholes used for ovality analysis.

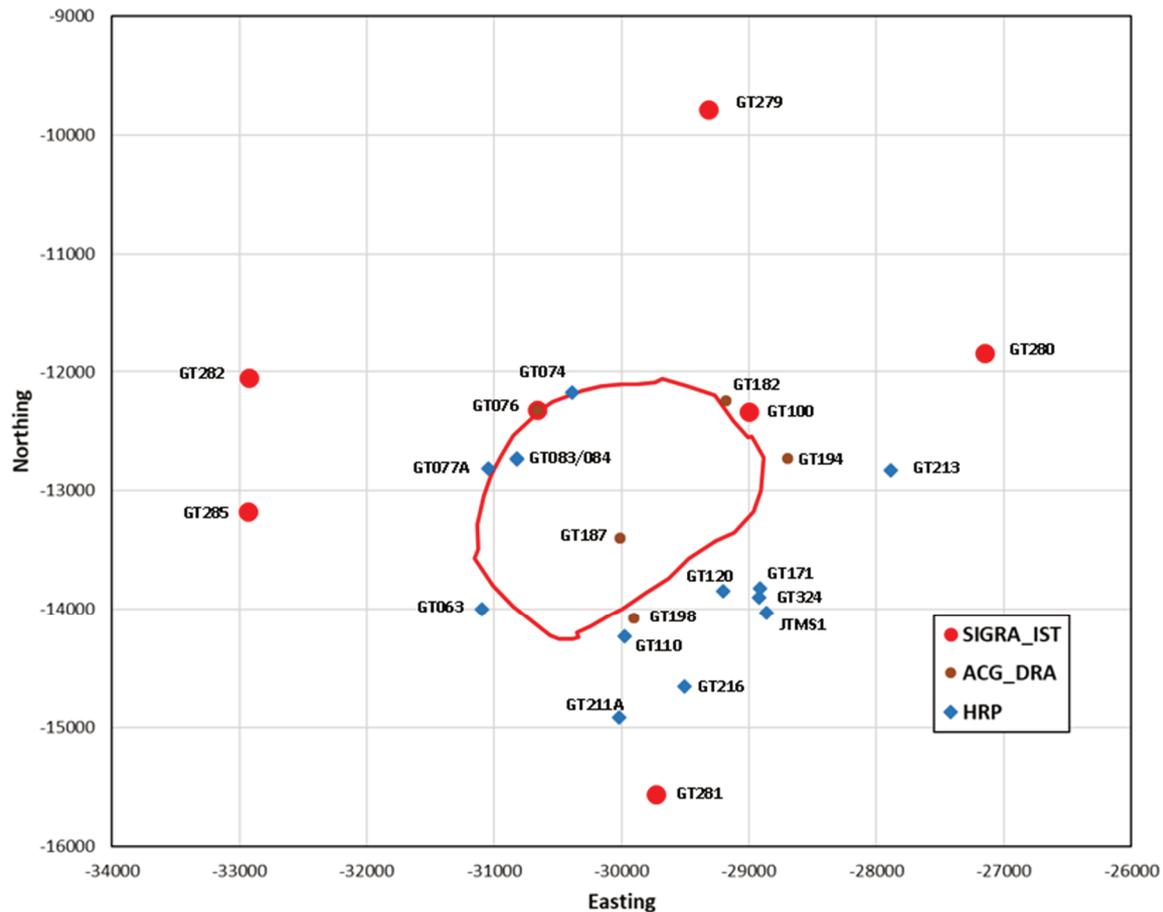


Figure 3 Sigra and DRA measurements as well as selected boreholes used for ovality analysis

3.1 Sigra in situ overcore

In situ stress test measurements were undertaken by Sigra using an overcore method. The overcoring method is a strain-relief stress measurement technique: the in situ stresses are estimated from the measured deformations induced in a rock volume by the removal of all stresses. The technique employed at Jwaneng Mine represents a variation of the time-proven method developed by the former US Bureau of Mines (Hooker & Bickel 1974). In the current application, the induced change of a 26 mm diameter pilot hole is measured, with 0.2 micron resolution, across six diameters offset 13 mm axially and 30° radially as it is removed from the surrounding stress field by coaxially coring an HQ sized hole. The tool is designed to operate at depth as part of a wireline operation and incorporates magnetometers and accelerometers for orientation measure accurate to 0.25° in three axes. Stresses are computed assuming that a purely elastic response is measured.

Since only diametral information is collected (no axial deformation recorded), results from multiple, non-parallel holes must be combined to constrain the complete stress tensor. Like hydraulic fracturing, the Sigra tool only measures stress components for the major (S_H) and minor horizontal (S_h) stresses in the plane perpendicular to the borehole. The vertical stress (S_V) component is assumed to be equivalent to the overburden.

Sigra conducted two stress measurement campaigns at Jwaneng Mine. In the first, undertaken in 2013, a total of 11 tests were attempted in two boreholes near the pit perimeter (Figure 3). Five tests were deemed successful, three in borehole GT076 and two in borehole GT100. The results from this campaign, as re-interpreted in 2019 (Stewart & Gray 2019), are presented in Table 2. The horizontal stresses are lower than

the vertical stress and the maximum horizontal stress is aligned northeast; this is different to the regional interpretation of the maximum horizontal stress orientation which is north-northwest–south-southeast.

Table 2 Summary of successful Sigra in situ stress measurements from 2013 (reprocessed in 2019)

Hole	Depth (mbgl)	Rock type	S_H (MPa)	S_h (MPa)	S_v (MPa)	S_H azimuth (TN)	Stress ratios $S_H/S_h/S_v$
GT076	425.15	QS	7.01	2.901	11.47	79.9	0.61/0.25/1
	518.85	QS	9.58	8.08	14.00	10.8	0.68/0.58/1
GT100	622.05	DM	10.4	4.2	16.78	28.6	0.62/0.25/1
	491.95	DM	19.56	12.07	13.27	38.2	1.47/0.91/1
	701.95	DM	18.88	17.22	18.94	346.1	1.00/0.91/1

In the latter part of 2019 extending into 2020, a second campaign was undertaken involving five boreholes remote from the existing pit (Stewart et al. 2020). These holes were GT279, GT280, GT281, GT282 and GT285 (see Figure 3). A total of 24 stress measurement tests were attempted, resulting in 11 successful measurements; no measurements were achieved in Holes GT279 and GT280. The results from this campaign are presented in Table 3.

Table 3 Summary of successful Sigra in situ stress measurements from 2019 and 2020

Hole	Depth (mbgl)	Rock type	S_H (MPa)	S_h (MPa)	S_v (MPa)	S_H azimuth (TN)	Stress ratios $S_H/S_h/S_v$
GT281	603.6	DM	22.06	11.87	16.28	161.1	1.35/0.73/1
	801.3	DM	13.31	12.29	21.62	46.4	0.62/0.57/1
	802.3	DM	12.91	11.45	21.64	19.3	0.60/0.53/1
GT282	712.6	QS	49.9	11.91	19.22	359.2	2.60/0.62/1
	911.1	QS	42.96	13.2	24.58	122.9	1.75/0.54/1
	912.1	QS	21.7	10.55	24.61	125	0.88/0.43/1
	1,003.2	DM	29.77	12.58	27.06	60.3	1.10/0.46/1
	1,007.4	DM	28.68	12.23	27.18	90.4	1.06/0.45/1
GT285	404.84	QS	6.18	5.19	10.92	137.4	0.57/0.48/1
	498.84	QS	30.36	13.55	13.46	95.3	2.26/1.01/1
	517.84	QS	16.06	9.27	13.97	40.9	1.15/0.66/1

These results generally support a horizontal stress less than vertical or thereabouts; two dominant maximum horizontal stress directions are present northwest–southeast and northeast–southwest. The northwest–southeast trend supports the regional trend (north-northwest–south-southeast) whilst the northeast–southwest trend is aligned with the major structure trend. Figure 4 shows the S_H orientations plotted on a stereonet; a considerable amount of scatter is observed.

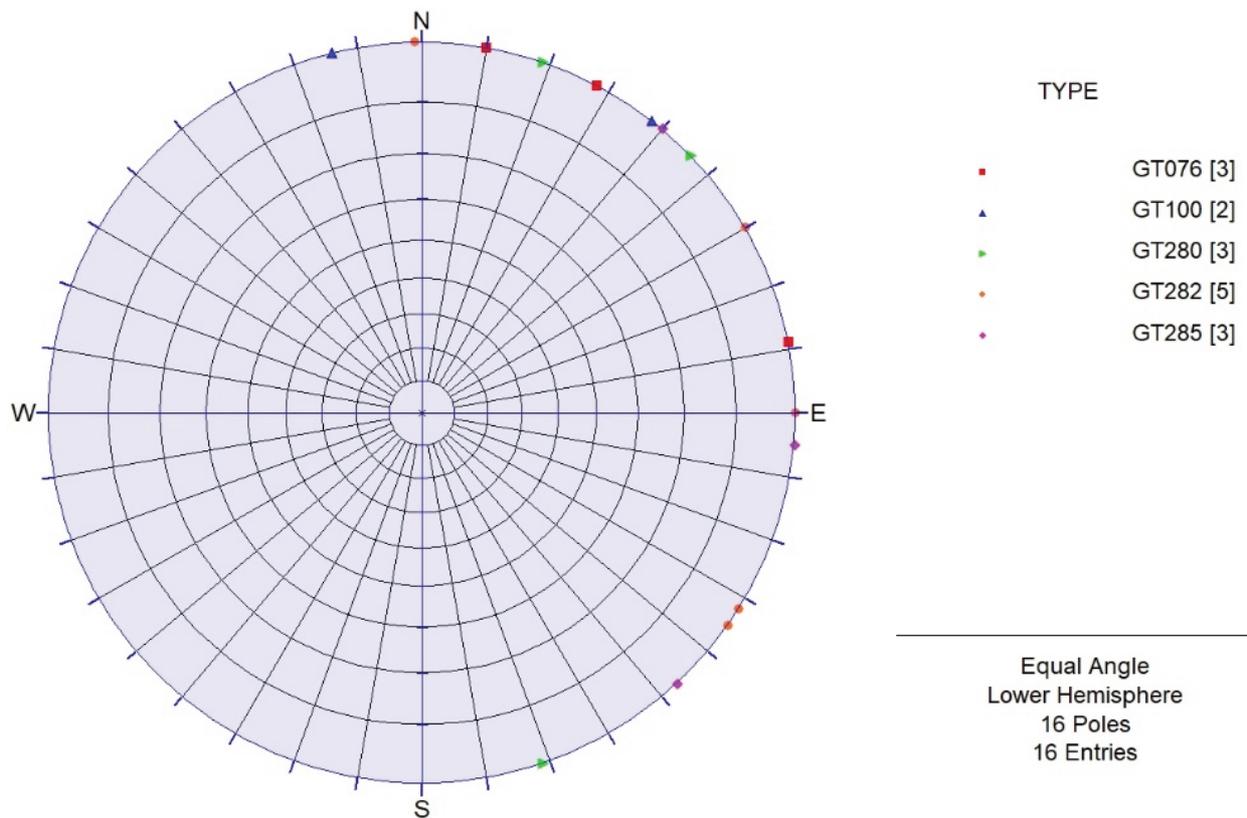


Figure 4 Stereonet with major horizontal (S_H) stress orientations from Sigra measurements

3.2 Deformation rate analysis

A total of five stress determinations were performed by the Australian Centre for Geomechanics (Dight & Hsieh 2019) on core recovered from five widely distributed boreholes, the locations of which are shown in Figure 3; Hole GT187 was within the pit, the others around its perimeter. It should be further noted that Hole GT187 was collared at an elevation of 849.44 m, some 330 m below the others. The reported results are provided in Table 4 and the orientations are shown in Figure 5.

Table 4 Summary of DRA stress measurements

Hole	Depth (mbgl)	σ_1 (MPa) @ trend/plunge	σ_2 (MPa) @ trend/plunge	σ_3 (MPa) @ trend/plunge	S_v (MPa)	Stress ratios $\sigma_1/\sigma_2/\sigma_3$
GT198	172.8	10.2 @ 276/06	6.2 @ 180/46	3.4 @ 011/44	4.66	3.0/1.8/1
GT187	387.4	16.6 @ 032/49	8.1 @ 284/15	5.8 @ 182/37	10.45	2.9/1.4/1
GT182	431.0	20.2 @ 341/10	14.4 @ 235/57	10.0 @ 078/31	11.63	2.0/1.4/1
GT194	432.0	18.2 @ 321/09	12.6 @ 201/73	8.8 @ 054/09	11.65	2.1/1/4.1
GT076	724.0	30.9 @ 348/10	20.4 @ 123/76	18.0 @ 256/11	19.53	1.7/1.1/1

The principal stress orientations determined in GT187 and GT198 are at odds with the others and with the generally accepted orientation for Southern Africa (north-northwest–south-southeast); they also both yield $\sigma_1:\sigma_3$ ratios some 50% higher than the others. In the case of GT187 this may be a result of its proximity to the kimberlite pipes. Overall, the K-ratios are significantly higher than indicated by the Sigra measurements and the generally understanding of stresses in Southern Africa.

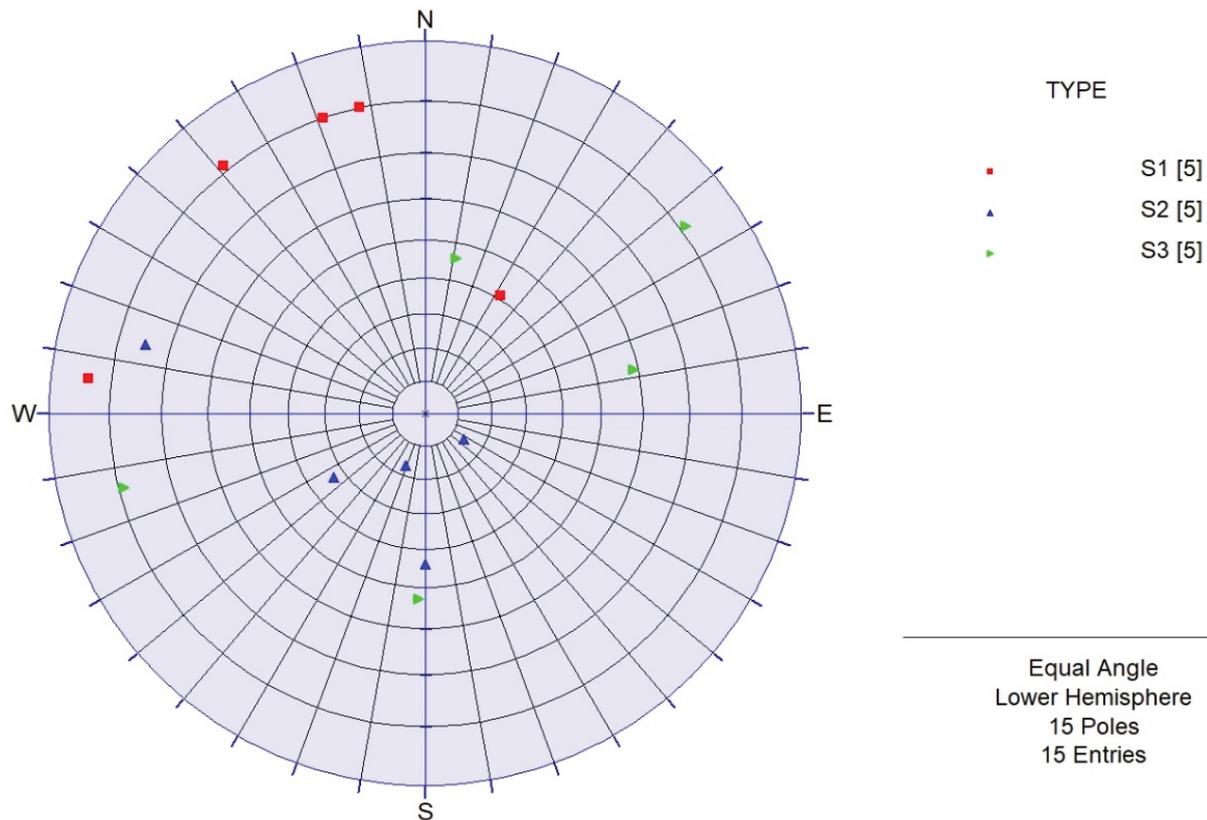


Figure 5 Principal stress orientations from DRA measurements (σ_1 – red; σ_2 – blue; σ_3 – green)

3.3 Borehole ovality

The response of the rock to the removal of the rock core when drilled is to deform under the ambient stress field. If the stress field is non-lithostatic, the borehole will assume an oval shape, the severity of distortion proportional to the stress ratio. The maximum closure will occur parallel to the major in-plane stress; the longer axis of the oval would then correspond to the minor stress orientation. By ascertaining the direction of the long axis, the orientation of the major lateral stress can be determined.

To accurately measure the borehole shape, acoustic televiwers (ATV) can be employed. These instruments transmit high frequency acoustic waves through the borehole fluid (typically water) and then record the return travel time and reflected amplitude. The former permits an accurate measure of travel distance, particularly when signal stacking is employed. The angular sampling frequency can be adjusted so that sufficient measurements are made to define the borehole perimeter. As the instrument also measures its 3D orientation, the radial measurements made are similarly oriented.

Harvey Rock Physics (HRP) use a proprietary technique modified from breakout work performed in Aleutian back-arc, Alaska (Zajac 1997) that allows the computation of the three stress components. Zajac (1997) uses breakout to identify the three components. In contrast, HRP modified the technique to calculate this as continuous curves denoting the orientation of the S1 (maximum horizontal stress), S2 (vertical stress, usually along hole) and S3 (minimum horizontal stress). To avoid confusion the following terms will be used: S_H , S_h , and S_v . When the hole is vertical, S_H and S_h are in the horizontal plane; for inclined holes they are perpendicular to the hole.

Two campaigns of stress orientation analysis were undertaken by Harvey Rock Physics (2020, 2021) using televiwer data. The first campaign considered 121 boreholes with televiwer records; 98 of these were deemed to be useable. This analysis was focused on identifying the major horizontal (S1 or S_H) and minor horizontal (S3 or S_h) stresses; this notation must not be confused with principal stresses. Typical outputs are

shown in Figure 6 and Figure 7. It should be noted that borehole breakout has not been observed in the boreholes used for the ovality analysis.

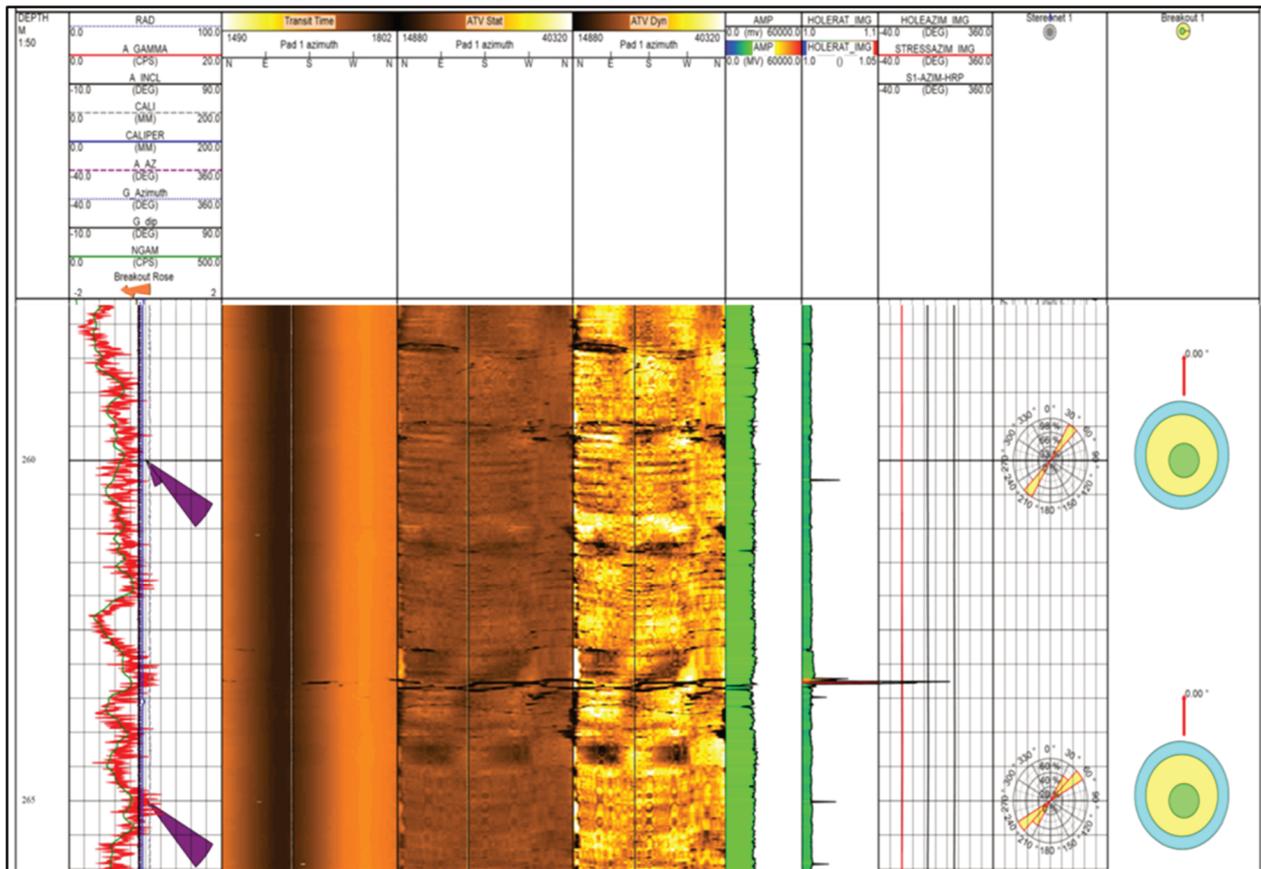


Figure 6 Example of ovality analysis outputs

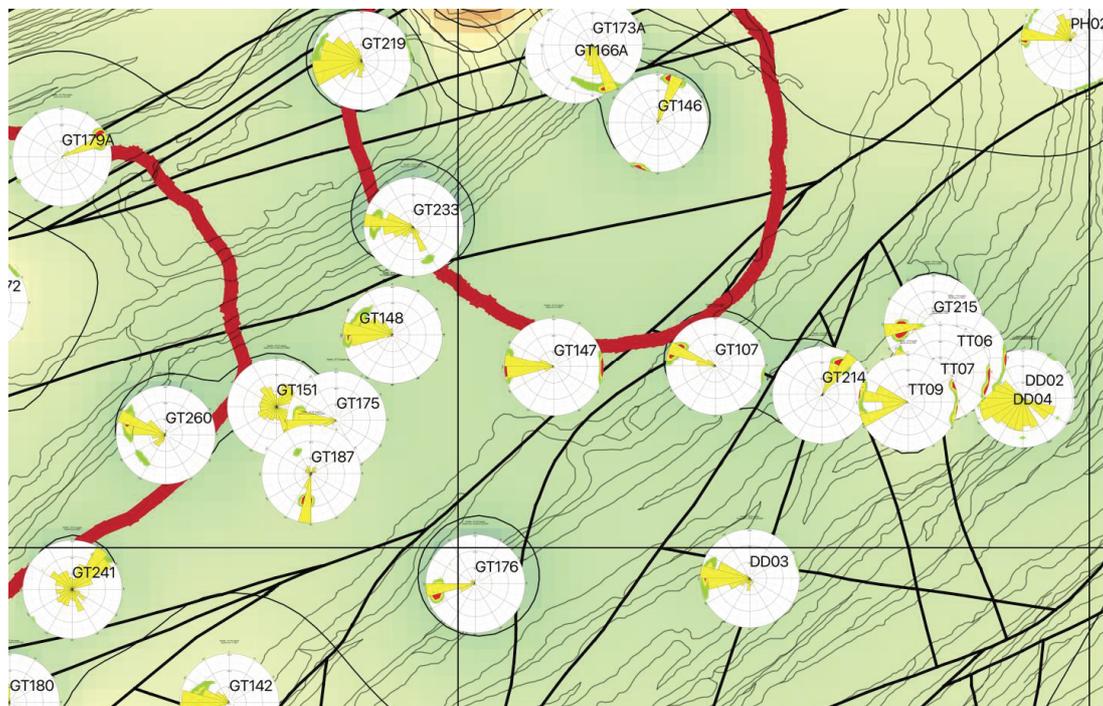


Figure 7 Excerpt from map showing a number of holes illustrating S_H (S_1) variability; close to faults (black) and near pipe edge (red) orientation changes

This analysis generally supported a northwest–southeast S_H orientation although there was considerable scatter. This was attributed to the complex structural environment, possible open pit influences and possible measurement errors or uncertainties associated with televiewer data capture, processing and subsequent interpretation in the ovality analysis.

Following an initial independent review of this analysis by Mirarco (Maloney 2020) and the Geotechnical Review Board (GRB); it was put forward that the large scatter in the result could be related to geological structures and open pit effects. Subsequently, the potential impact of the open pit on stress orientation was assessed inhouse (Harris 2022). This was done by identifying drill holes used in the ovality analysis that were potentially influenced by the pit. The holes were plotted in three-dimensional space and were compared to the as-mined pit shell for the year in which they were drilled. Halos around the pit shell were defined and this allowed data to be separated and winnowed out, allow for comparisons between data that may have been influenced by open pit mining and more distal data.

The maximum horizontal stress azimuths were analysed for different drillhole intervals using histograms and Radar plots. Initially 67 boreholes were assessed in this manner; 10 holes were then excluded. Of the remaining 57 boreholes, only five (9%) showed a definite open pit influence whilst ~56% showed no influence and the remainder (~35%) showed a possible influence. This analysis is considered inconclusive due to the scatter in the data and possible influences of major faults and proximity to kimberlite pipes. The data indicated two dominant S_H directions, the more dominant northwest–southwest which coincides with the WSM and a northeast–southeast trend which coincides with the general trend of the major structures and may reflect a stress rotation.

A second campaign of ovality analysis was undertaken in 2021; this was a more focused campaign, targeting the three holes used for the second Sibra (2019–2020) campaign so that direct comparisons could be made. An additional seven holes distal from the open pit were also included. Comparison with the Sibra data indicated that there was a good correlation in the S_H orientation for five of the 11 measurements compared. The ovality data generally indicated a west-northwest to east-southeast orientation.

4 Interpretation stress data

Various methods have been used to assess estimate stress magnitudes and orientations over several years for Jwaneng Mine. Considerable variations in the data are observed and there are contradictory and conflicting results; making interpretation challenging. To assist with interpreting the results, Debswana has made use of an independent GRB and technical experts. This approach has been implemented over several years and is ongoing.

4.1 GRB 2018

The Underground GRB has been in place since 2018 and advises on what stress measurement work should be undertaken as well as reviewing and assisting with interpretation. In 2018 the GRB suggested that currently the prevailing stress state is not horizontal stress dominated. This was based on a review of the Sibra data, inferences from Creus et al. (2017) that the latest era (i.e. current) prevailing geological stress regime is northwest–southeast extensional, and also the back-analysed most likely stress state for the fault mechanism thought responsible for the deep crustal April 2017 earthquake is also northwest–southeast extensional.

The GRB also indicated that clarification was needed on stress variability across the site and with depth as the Sibra stress results, when examined in terms of magnitude and direction and compared with palaeostress back-analysis results for the fault structures at Jwaneng, are clearly pointing to multiple complications in the stress field with depth, with possibly four major influences needing to be considered for future mine planning and numerical modelling purposes:

- Pit influence effects.
- Fault structure influence effects.

- Remnant D2 rotated northwest–southeast compressional effects.
- Likely current northwest–southeast D3 extensional effects.

It was indicated that the stress data suggests that there may be two distinctly different stress regimes existing within different fault blocks in and around the kimberlite pipes at Jwaneng and this needed further investigation.

4.2 MineGeoTech (2020) review

Lee (2020) on behalf of MineGeoTech, undertook a review of the results from the first Sigra campaign (2013 reprocessed in 2019) and the DRA results and compared these measurements to the present understanding of stresses within the broader region and the South African gold and platinum mines. The following were considered in this review:

- Is the measurement reliable?
- Were the measurements done competently?
- What confidence can be placed in the in the quoted results?
- How do the results relate to the local geology, particularly the local structures?
- How do the results fit with the regional understanding of Southern African stresses?
- Can we confidently use this data for mine design?

Lee (2020) noted that strain-relief (overcoring) and hydraulic fracturing are generally considered the only two reliable methods that should be used for design for design but that there are challenges doing these measurements in deep boreholes in a stiff rock mass. Rock stress estimation techniques based on cores (acoustic emission and DRA) do not share the same confidence.

It was concluded that despite the five good Sigra measurements; these only achieve the confidence of one good site result for overcoring CSIRO HI-cells. The Sigra data was interpreted as follows:

- σ_1 = overburden stress and is vertical.
- $\sigma_2 = 0.6\sigma_1$ oriented north-northeast–south-southwest.
- $\sigma_3 = 0.4 \sigma_1$.

This stress field is only applicable to the county rocks away for the kimberlite pipes.

The DRA results were not considered reliable for design and were interpreted as follows:

- $\sigma_2 \sim \sigma_3$ = overburden (σ_2 was sub-vertical).
- $\sigma_1 \sim 1.6 \times$ overburden and oriented northwest–southeast and is flat dipping.

Following comparisons with the regional stress field, Lee (2020) recommended the following:

- K-ratios of 1.0 : 0.7 : 0.5 for $\sigma_1 : \sigma_2 : \sigma_3$.
- σ_1 is sub-vertical and equivalent to overburden.
- σ_2 is the maximum horizontal stress and oriented north-northeast–south-southwest.

4.3 Mirarco review (2020)

Mirarco (Maloney 2020) undertook a review that included data from both Sigra campaigns, DRA measurements and the ovality data analysis. Mirarco were able to make comparison between the maximum horizontal stress trend from the Sigra (first campaign) and DRA measurements and the ovality data. Generally, a significant amount of variability was observed in the orientation data especially the ovality data,

which had a good deal of scatter (Figure 8). The measurements suggest that the trend of the major horizontal stress is quite variable, both along any given hole and between holes.

To some extent, the variability can be attributed to the influence of adjacent or intersecting structural features. The average principal horizontal stress orientation, as determined from borehole ovality in the reviewed logs, was east-northeast although from hole to hole it varied widely, ranging from north to south-southeast. This orientation corresponds roughly with the general trend of the major faulting at the Mine (Maloney 2020). The overall trend, as reported from consideration of all the measurements, is different at west-northwest which is slightly off the Southern Africa trend of north-northwest–south-southeast suggested by Andreoli et al. (2015).

The Sigra data was interpreted to indicate that the vertical stress was the major stress when the horizontal stresses (S_H and S_h) were compared to the S_V ; the DRA data was contrary to this. Mirarco noted that there are few stress measurements recorded in the public domain for Botswana, let alone in the vicinity of Jwaneng Mine. Manzunzu et al. (2019) based on earlier work by Meghraoui et al. (2016) provide a summary of stress states in Southern Africa based on reviewed stress data; this indicates that measurements surrounding Jwaneng, although not in close proximity, reflect a normal faulting environment (i.e. vertical stress dominant) with the major horizontal stress oriented north-northwest. This is consistent with the measurements made at the mine if allowance is made for redirection to align with the faulting.

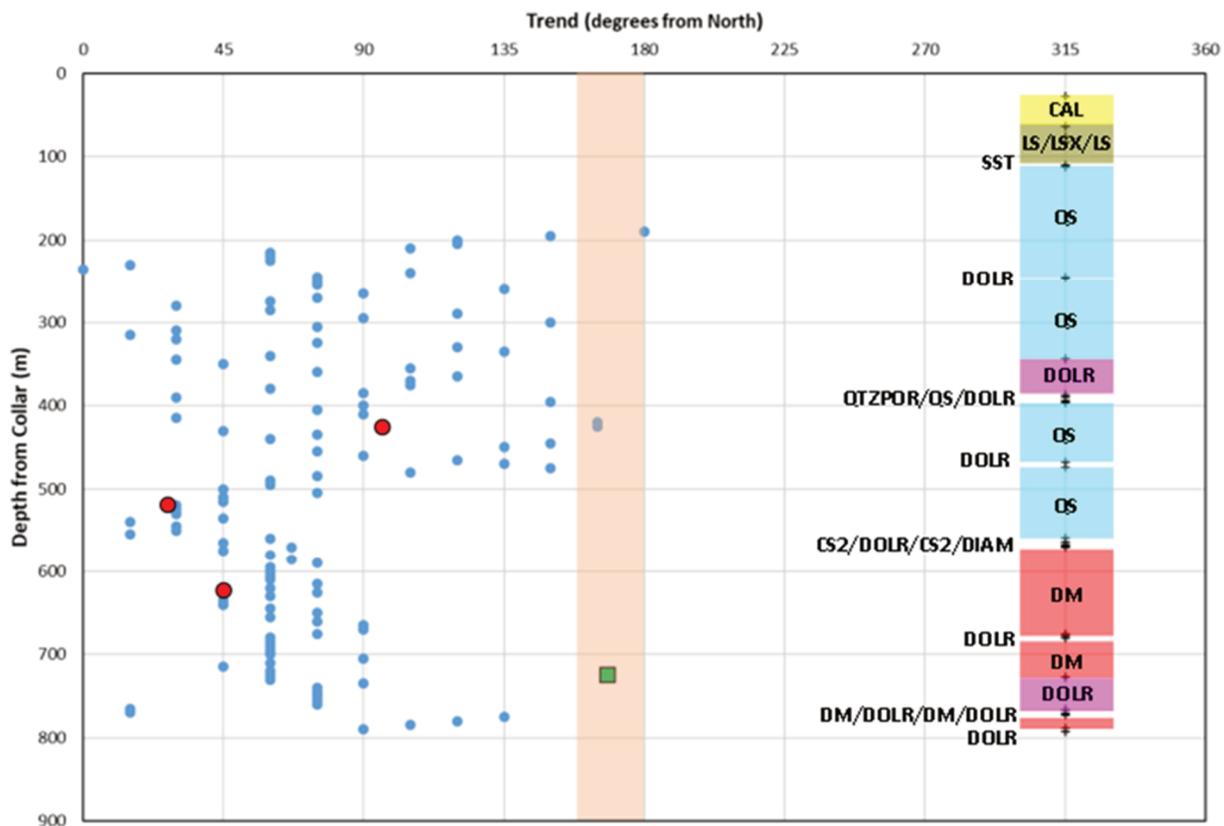


Figure 8 Stress orientations determined from overcoring (red circles), DRA (green square) and borehole ovality (blue dots) in hole GT076; shaded zone represents the generally accepted major stress orientation for Southern Africa (north-northwest–south-southeast)

In terms of observations of stress related issues in mine development, there are no records of stress-induced instability of the mine workings that would suggest high lateral stresses. Evidence of such, if present, could include violent fracturing behind the bench face and borehole offsets (Stacey 2007) or buckling of the pit floor (Wallach et al. 1995; Adams 1982). The only failures documented have been related to gravity driven slips on steeply dipping bedding daylighting into the pit (Venter et al. 2019). Mirarco indicated that the pit behaviour, seismic record and surrounding stress measurements all support an environment in which the

major principal stress is vertical or thereabouts. There is no evidence of pervasive, high lateral stress conditions although they may develop locally due to other factors. Hence, the external evidence validates the results of the overcoring measurements.

Mirarco (Maloney 2020) made the following conclusions:

- The stresses in the host rock at Jwaneng Mine reflect the geological environment and are quite variable both in terms of magnitude and orientation. They are strongly influenced by the numerous faults, shears, intrusions and likely by mining activities as well. Generally, away from the kimberlite pipes and major geological structure, the stresses are consistent with a normal faulting environment ($S_v > S_H > S_h$). However, locally, in the vicinity of local faulting, the major horizontal stress can be exaggerated, becoming the major principal stress.
- In terms of magnitude, the best fit stress state can be summarised as: $\sigma_1 = \sigma_v$, $\sigma_2 = 0.9\sigma_1$ and $\sigma_3 = 0.5\sigma_1$; this is not dissimilar to that defined by Lee (2020).
- In general, the major horizontal stress is oriented to the east-northeast. This is at odds with the overall trend for Southern Africa of north-northwest–north and possibly reflects a local phenomenon where the stresses have been diverted to roughly align with the major faults intersecting the site. More measurements and numerical modelling would be required to validate this hypothesis.
- The measurements obtained from overcoring were the most reliable even though they were not without issues. For greater confidence in such measurements, multiple measurements should be conducted in proximity and in sites free from potential stress modifiers.

4.4 GRB review (2020 and 2021)

The GRB also assessed the results and provided feedback. It was concluded that there was significant variation in the stress measurements and subsequently uncertainty around the stress field tensor. This has necessitated the use of two stress tensor interpretations and the inclusion of sensitivity analysis in numerical modelling and future design analysis. The possible stress field tensors are shown in Figure 9 and summarised in Table 5.

The GRB also made recommendations for additional ovality analysis to be undertaken on boreholes from the second Sigra campaign and holes distal from the open pit (actioned) and a more detailed assessment of the stress state (being undertaken).

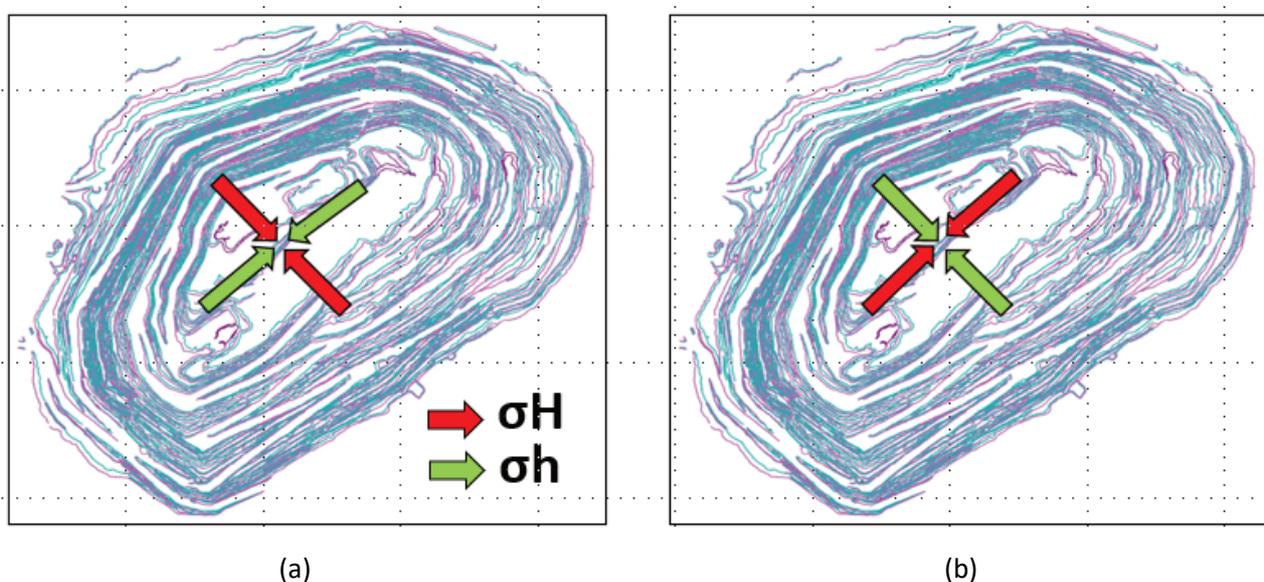


Figure 9 Possible stress field tensors. (a) Option 1; (b) Option 2

Table 5 Possible stress field tensors

Stress field	σ_H	σ_h	σ_v	σ_H azimuth
Option 1	$1.1 * \sigma_v$	$0.5 * \sigma_v$	$\sigma_v \sim \text{depth (m)} * 0.027(\text{MN/m}^3)$	340 (northwest–southwest)
Option 2	$0.9 * \sigma_v$	$0.5 * \sigma_v$	$\sigma_v \sim \text{depth (m)} * 0.027(\text{MN/m}^3)$	215 (northeast–southwest)

5 Discussion

Understanding the stress field is critical for underground mine design where the rock stress to rock strength ratio may be unfavourable. There are a variety of ways in which stress magnitude and orientation can be assessed; however, during the study stages prior to underground access there are only a few options available (DRA, AE, Sigra IST etc.). Once underground access is available, measurement by overcoring using triaxial stress cells (CSIRO or ANZI) can be undertaken to reliably measure the full in situ stress tensor with sufficient redundancy.

As an alternative to overcoring in deep hole applications, consideration should be given to employing hydraulic tests on pre-existing fractures (HTPF). This technique utilises existing drill holes and is more robust in terms of interpretation than conventional hydraulic fracturing. Furthermore, it provides a direct measure of stress. The principal limitation is finding sufficient, suitable joints/faults of varied orientation within a representative volume.

There are also difficulties associated with comparing stress measurements for different measurements methods. The DRA method produces principal stresses whilst the Sigra and Borehole Ovality methods deal with major and minor horizontal stresses and the assumption that the vertical stress is equivalent to the overburden. This complicates the interpretation and comparison of the results, specifically with respect to the magnitudes and stress ratios.

All stress measurement methods have limitations and associated uncertainties it is possible to get poor or unreliable results, and this is well documented in the literature. Wiles (2006) notes that “Several hundred precision, temperature-controlled HI cell (CSIRO hollow inclusion cell) measurements were made at Canada’s URL (AECL underground research laboratory). Analysis of these very high-quality measurements demonstrates that the coefficient of variation for stress magnitude is in the order of 20%.... One could expect even higher variability at sites where the rock mass is not as uniform as at the URL”.

In addition to issues associated with the measurement methods there is also the influence of stress modifiers such existing excavations and geological structures such as faults, kimberlite pipes, sills and dykes. In a complex geological environment such as Jwaneng Mine it is difficult to avoid the possible influence of major structures, and this has likely resulted to stress rotations and the possibility of two distinct stress fields within different fault blocks.

At this stage the stress field in the pipes is largely unknown, although the general view is (Jakubec & Van As pers. comm. January 2020) is that it would be lower than the country rock. Reusch et al. (2008) stated that at Panda Mine and in many volcanic pipes, the stress is lower in the pipe because of the mechanics of pipe emplacement. Due to drilling activities associated within weak kimberlite and core retrieval, the in situ stress in the pipes can only be assessed once there is underground access.

All stress measurements are point measurements and reflect the stress state at the point of measurement. Several stress measurements distributed in three-dimensional space are required to get a full appreciation of the mine-wide stress state; there are cost and practical limitations to doing this. Borehole ovality analysis allows for thousands of stress direction estimates to be undertaken across the mine site but this method is associated with a high degree of scatter. It is uncertain whether this is real or an artifact of the method or both.

Work is ongoing with further review by Mirarco and development and calibration of a large-scale model to back analyse the point stress measurements and derive appropriate boundary conditions for future numerical modelling.

Given the various uncertainties outlined above, it is prudent to use several measurement techniques; it is also necessary to interpret all stress measurement in terms of the site structural geology and the broader geological and stress setting. This is not an easy task, and the use of expert independent reviewers is beneficial. Even after doing all of this, it is likely that some uncertainty remains and the use of sensitivity analysis in numerical modelling design analysis is recommended.

6 Conclusion

Debswana recognises that understanding the stress field is a critical input into the Jwaneng underground project studies and has a significant impact on the underground mine design. Considerable effort has gone into making stress measurements using different techniques. This has been backed up with a comprehensive review of the literature pertaining to the regional stress state as well as independent review and guidance by the GRB and Mirarco.

It is recognised that there is still uncertainty; thus, sensitivity analysis for the stress field is used when undertaking numerical modelling. Work is ongoing and the work summarised in this paper is considered as the first leg to understanding the stress state at Jwaneng Mine.

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