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Implementation of an effective depressurisation program in the structurally complex Jwaneng diamond mine

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Abstract

The Jwaneng Mine is a large open pit diamond mine with a planned depth of approximately 850 m from the current pit depth of approximately 500 m. The major geologic units at the mine include 500 m-thick low-permeability shale that overlies the massive dolomite. The upper portion of the dolomite is more permeable than the underlying dolomite. Extensive geologic structures are present at the pit and in its vicinity, which causes complicated compartmentalised groundwater flow conditions. The presence of these geologic structures affects both bench-scale and large-scale slope stability, thus requiring active dewatering and depressurisation to avoid pore-pressure-induced failures. In-pit dewatering and depressurisation have proved to be more feasible and effective for these low-permeability rocks and compartmentalised groundwater conditions in the Jwaneng Mine. The highly active and constrained production spaces and dynamic mining plans pose logistical challenges for the optimal implementation of permanent in-pit dewatering infrastructures. Implementation of dewatering and depressurisation requirements at the Jwaneng Mine are guided by empirical data on the mine and the outputs of the well-calibrated numerical groundwater flow model. The recent installations of dewatering infrastructures include inclined dewatering wells intended for mobile dewatering, pit floor drain holes for continuous passive dewatering, and horizontal drain holes on the pit surface to intercept any perched water in the remediated bench-scale failure areas. To assess the effectiveness of the dewatering and depressurisation, efforts have been made to monitor the groundwater levels within 200 m behind the pit wall. These monitoring data are critical for assessment of the effectiveness of the depressurisation effort, and the effect of rainfall and of zone of relaxation on the pore pressure distribution. With the combination of different dewatering approaches, monitoring, and the numerical model, the Jwaneng hydrogeology team has been able to achieve the depressurisation targets since 2013.

Keywords: *depressurisation, slope stability, pore pressure, borehole nuclear magnetic resonance, hydraulic conductivity, groundwater modelling*

1 Introduction

The Jwaneng Mine is located 120 km west of Gaborone in Botswana. The land-surface elevation in the mine area is approximately 1,175 metres above mean sea level (mamsl). The mine began operations in 1982 as a single open pit. The pit has been developed and will continue to be developed with various mining stages that are referred to as 'cuts'. Future mining consists of Cuts 7, 8 and 9. The bottom elevation of the final pit will be approximately 350 mamsl by 2033, which is approximately 850 metres below ground surface (mbgs). Because of the large depth of the pit, effective dewatering and depressurisation of the pit slope is required to reduce the pore pressure and enhance slope stability. This paper describes the effective depressurisation strategy and system that has been implemented at the mine.

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2 Hydrogeologic setting

The conceptual hydrogeologic model is illustrated in Figure 1. As shown in Figure 1, the groundwater regime at the Jwaneng pit is controlled by a highly complex structural setting within a hydrostratigraphy dominated by lithological units of low hydraulic conductivity (*K*). These lithological units consist of laminated shales and quartzitic and carbonaceous shales from about 50 mbgs to depths of 400–500 mbgs, where dolomitic units are present. Figure 1 shows the following key geologic features that affect the pit depressurisation:

1. The top 50 m from the surface is occupied by the Kalahari unit, which has no significant hydrogeological importance except to act as a pathway for recharge either from rainfall or mine facilities like tailings dumps, slimes dams, unlined ponds and areas around the ore treatment plants. This unit is dewatered to minimise flow from sources through the so-called scavenger wells.
2. The presence of thick low-permeability rock that overlies the dolomite requires a combination of dewatering boreholes, sub-horizontal drain holes, and sub-vertical drain holes.
3. The dolomite dips from southeast to northwest. At a regional scale, dolomite that outcrops at the ground surface is a prolific aquifer. This is mainly due to fracturing and subsequent karstification, which allows recharge through these conduits. The future pit will encounter the dolomite, and thus, dewatering of the dolomite will be required.
4. Limited boreholes that have intersected the dolomitic unit through the various resource definition projects do not indicate the same characteristics for dolomites at depth below the Jwaneng pit, except at the brecciated contacts with the kimberlite bodies, where appreciable yields of up to 4,080 cubic metres per day (m^3/d) have been encountered.

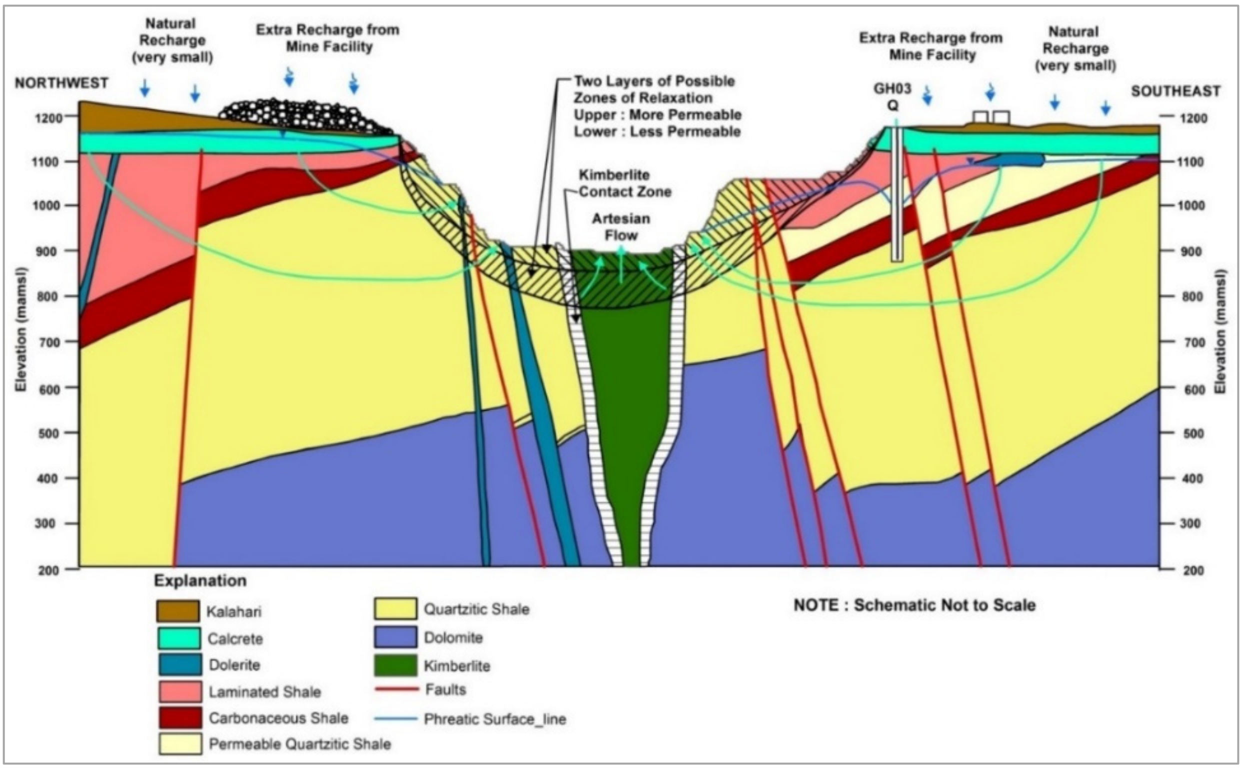


Figure 1 Cross-section showing the conceptual hydrogeological model of the Jwaneng pit

The fundamental equation that guides dewatering requirements is given by Equation 1:

$$\Delta h(x,t) = \Delta h_0 erfc^{-1}\sqrt{\left(\frac{4Kt}{S_s x^2}\right)} \tag{1}$$

where:

Δh = change of hydraulic head

K = hydraulic conductivity

S_s = specific storage

t = time

x = distance from the dewatering point.

This equation follows from the step offset impulse response solution for a semi-finite confined aquifer (Hermance 1999). The equation allows one to quickly evaluate the dewatering requirements assuming homogeneous isotropic conditions. For a robust evaluation of the same, given heterogeneous anisotropic conditions (which are almost always the norm in a large aquifer domain), one then must resort to numerical modelling.

The parameters K and S_s are properties of the aquifer, whereas x and t are space and time factors, respectively. For quick qualitative evaluation of the equation, a larger drawdown is achieved for large K and t parameters, and the converse is true for large S_s and x values. To put this in perspective for the Jwaneng Mine, given the low hydraulic conductivities (1×10^{-4} to 1×10^{-5} metres per day [m/d]) for the prevailing rocks, it requires that depressurisation starts well ahead of mining and should be done in very close space or inside the pit in order for it to be effective.

3 Current dewatering infrastructure

The dewatering infrastructure in 2012 comprised of 5 dewatering wells at an operational capacity of 1,200 m^3/d and 7 pore pressure monitoring points. With guidance from Equation 1 and the low hydraulic conductivity environment, one can quickly deduce that the dewatering wells were likely not to be able to effectively depressurise the pit. As a result of this inadequacy, a huge dewatering program was embarked on towards the end of 2012, to ramp up the dewatering system for effective depressurisation performance.

The current (2025) infrastructure at the Jwaneng Mine has been implemented following the decision to ramp it up in 2013. The current system is made up of 28 ex-dewatering boreholes operating at a total of 130 m^3/hr. All these boreholes are equipped with variable speed drives (VSDs) to optimise pumping performance and are connected to a remote data acquisition system to monitor both the mechanical and hydrogeological parameters. The data acquisition system allows real-time as well as historical performance and trend analysis. In addition to the dewatering boreholes, 64 sub-horizontal boreholes are installed on the pit slopes. Several vertical to inclined drains have also been drilled to help depressurise the toes and kimberlite/country rock contacts. Grouted multi-level (nested) vibrating wire piezometers (VWPs) are used for pore pressure monitoring to allow evaluation of the dewatering system performance. Currently, there are 71 multi-level VWPs collared around the pit, with 26 installed in the pit. In total, there are about 200 measuring points from these multi-level piezometers, and all are monitored via a remote real-time data acquisition system.

4 Development of the dewatering strategy and plans

Numerical groundwater flow and geomechanical stability models for the pit play important roles in the development of any dewatering program, and the Jwaneng Mine is no exception. Three-dimensional (3D) slope stability analyses were conducted for different mining stages in terms of Factor of Safety (FoS) contours, as shown in Figure 2 for the Cut 8 pit shell. The target phreatic surface is obtained from the stability analyses once the pit design meets the required FoS (within 1.2–1.3).

By using the simulated phreatic surface from the groundwater flow model as the reference phreatic surface, the target phreatic surface for different mining stages (Figure 3a) was determined with the following steps of the 3D slope stability analysis:

1. Slope stability analyses are carried out by first assuming a depressurised water condition defined by Hu=0.25, which is used to validate the mine pit design. At this stage, alternative mine pit designs may be needed if the acceptability criterion is not met (0.25 in Figure 3b and Table 1).
2. After Step 1, the reference phreatic surface was lowered by various depths (20 m and 25 m in Table 1) with a Hu value of 1 (hydrostatic condition) to reproduce similar FoS results to Step 1.
3. The phreatic surface in Step 2 was considered as the target phreatic surface.

Based on the slope stability analysis, the target phreatic surfaces were derived for different mining stages, which were used to plan for future dewatering and depressurisation.

The target phreatic surfaces obtained for each mining stage are used as references in the 3D groundwater flow model simulations, where the dewatering infrastructure is implemented and tested until achieving those targets. These interactions between the geomechanical model and the groundwater flow model are critical to achieve the required FoS for the slopes at different mining stages.

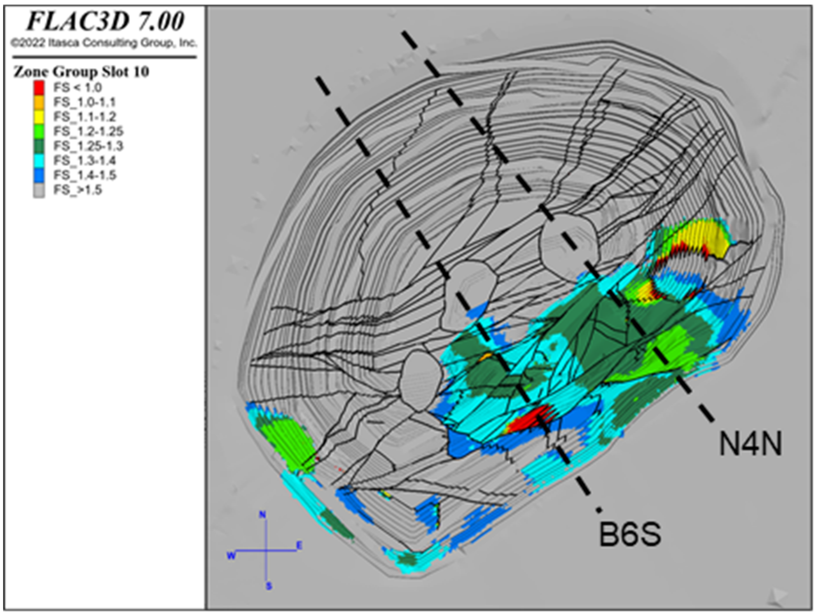
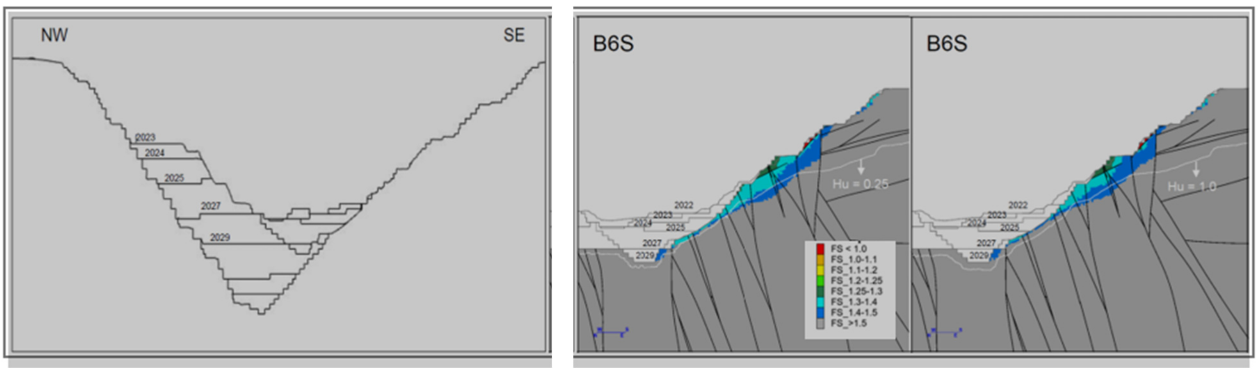


Figure 2 Factor of Safety contour from three-dimensional slope stability analysis for the Cut 8 pit shell



(a) (b)

Figure 3 (a) Mining stages along cross-section B6S; (b) Target phreatic surface superimposed on the Factor of Safety contours for the final Cut 8 wall

Table 1 Comparison of FoS results with Hu of 0.25 and the target phreatic surface for the 2025 and final Cut 8 walls (header such as B6_1 refer to design section)

2025 – Factor of Safety (FoS)					
	B6_1	**B6_2**	**N4_0**	**N4_1**	**VK_S**
Base case (Hu = 0.25)	1.25	≥1.5	1.25	1.25	1.2
Hu = 1.0 (d = 25 m)	1.25	≥1.5	1.25	1.3	1.25
Hu = 1.0 (d = 20 m)	1.25	≥1.5	1.25	1.3	1.25
Cut 8 – FoS					
	B6_1	**B6_2**	**N4_0**	**N4_1**	**VK_S**
Base case (Hu = 0.25)	1.25	1.25	1.25	1.25	≥1.5
Hu = 1.0 (d = 25 m)	1.25	1.3	1.25	1.3	≥1.5

The above analysis guided the groundwater flow simulations to predict the depressurisation infrastructure that is required to achieve the target pore pressures. As a result, additional depressurising infrastructure is required to achieve the target water-level profiles for each mining stage. Each design section was defined based on the groundwater flow model simulation (Figure 4). Additional infrastructure included sub-horizontal drain holes averaging about 200 m in length, installed at the different mining stages. A few in-pit boreholes were required from 2024 at the toe of each design section following the phased approach. Figure 4 shows details for the simulated infrastructure to be installed from 2024–2025.

The development of dewatering requirements therefore requires a lot of interaction between the geomechanical and hydrogeological teams followed by developing a plan of implementation, which requires funding for infrastructure installation. So, the next step is to apply for funding, and hence, there is a need to present a robust business case to the investors through the finance and project departments.

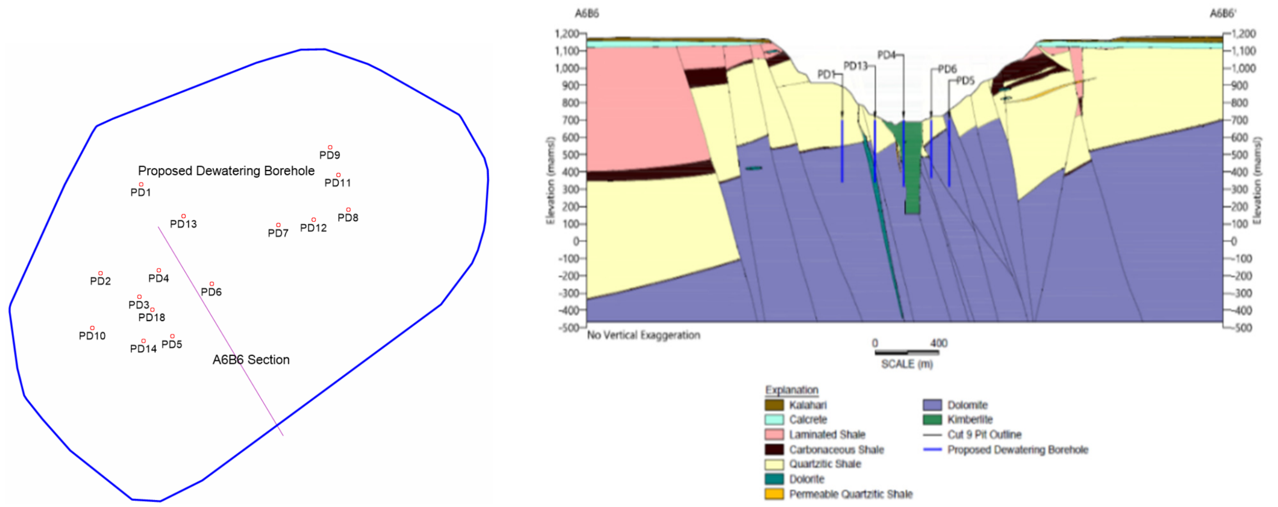


Figure 4 Simulated dewatering infrastructures along design section A6B6 to achieve the water levels required by a Factor of Safety of 1.2 for the final Cut 8 slope

The Jwaneng Mine follows a phased approach dewatering plan, which is quantitatively informed through the work explained above. Phases I–IV have already been completed, and the mine is now at the early stage of implementing Phase V. Mining of Cut 9, which is mainly in the western side of the pit (due to the split shell mining approach) will undercut Cut 8 slopes at certain locations; hence, the Phase V action plan takes into account both the Cut 8 and Cut 9 slopes. The long-term dewatering plan goes up to 2035.

Placement of additional infrastructure up to 2026 will be continuously refined using the information derived from performance reviews of the existing installations. Beyond the pit depressurisation project Phase V, it is planned that the dewatering action plan will focus on drilling some more sub-horizontal holes in lower stacks of Cut 8 as well as installing in-pit dewatering boreholes. This plan is illustrated in Figure 5.

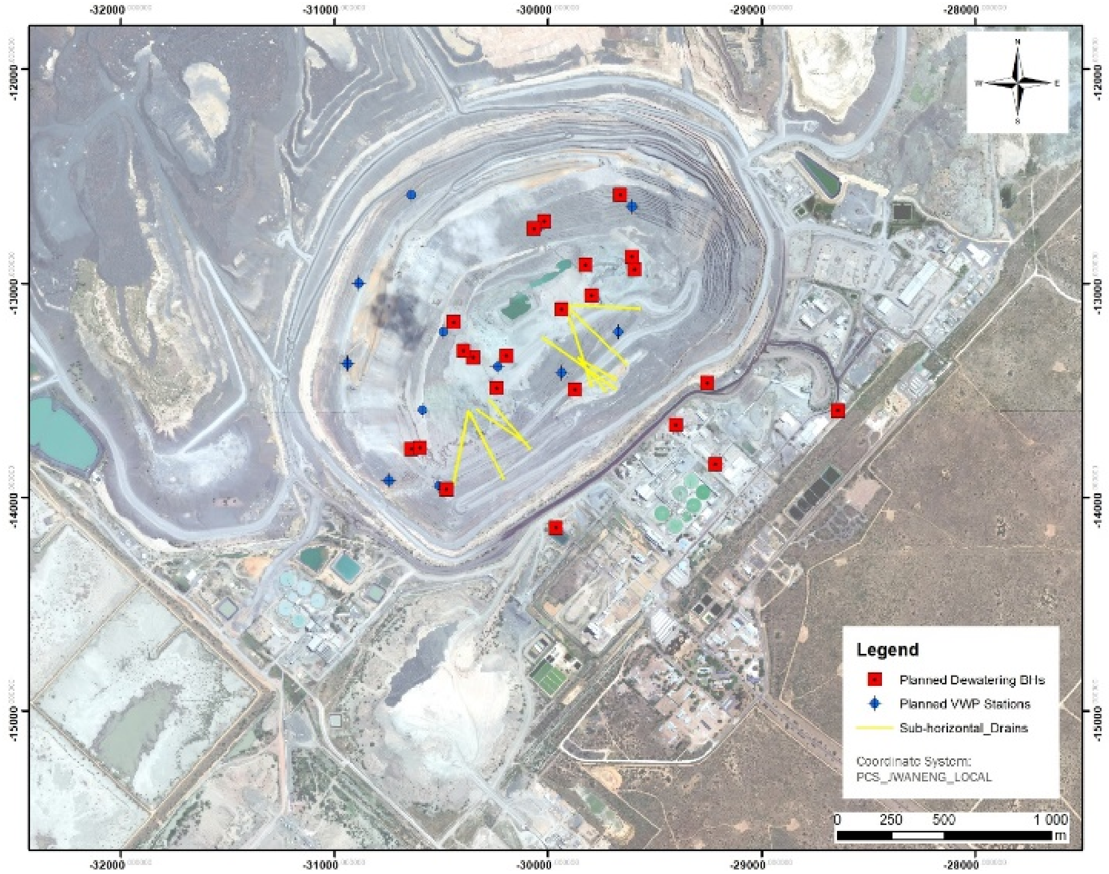


Figure 5 Dewatering plan for the years 2023 to 2026 to be implemented through the pit depressurisation Phase V project

5 Enhancement of the dewatering strategy

The main strategy of developing an optimal dewatering infrastructure has been outlined in Sections 3 and 4. However, an active mining pit such as the Jwaneng Mine is often inundated with multiple operational undertakings competing for the limited space inside the pit. This poses a risk at both the implementation and operational stages of effective dewatering infrastructures. In addition to that, the groundwater flow is strictly fracture controlled, and hence, there is a need to accurately locate target structures for optimal groundwater extraction. The mine is a built-up area and, hence, poses a lot of anthropogenic noise that limits the exploitation of conventional geophysical techniques like horizontal loop electromagnetic (HLEM), electrical resistivity tomography and seismic refraction surveying methods to locate such structures.

In order to deal with these risks, the hydrogeology team at the Jwaneng Mine is exploring various technologies and opportunities to achieve the depressurisation objectives, in addition to the execution of the planned dewatering program.

5.1 Exploitation of the borehole nuclear magnetic resonance technique

As already alluded to in Sections 2 and 3, the prevalent rocks at Jwaneng are of low hydraulic conductivity, and groundwater flow is strictly fracture controlled. Targeting permeable fractures is therefore imperative for pit slope depressurisation. It is important to target large, permeable structures for effective depressurisation (Beale & Read 2014). Targeting small-scale fractures for pumping is not effective, as the bulk of the flow passes through to the pit. The reverse is true for large-scale open fractures.

Since 2016, Jwaneng Mine geoscience team have adopted an integrated approach where borehole geophysical data including televiewer, Full Wave sonic, borehole nuclear magnetic resonance (bNMR) are routinely interpreted to delineate highly conductive zones. The bNMR technology is particularly used here to characterise the hydraulic properties of the fracture zone. It is widely used in both petroleum exploration and hydrogeological studies as summarised by Freedman (2006), Akkurt et al. (2009) and Allen et al. (2000).

Figure 6 shows drainable water zones identified by the bNMR technique along one of the boreholes, which were corroborated by another geophysical technique, acoustic televiewer (ATV). Whilst the televiewer tools can map open fractures with a high degree of confidence, the hydrogeologic characteristics of that fracture can be determined from the bNMR technology, complemented by fullwave sonic logs. Piezometric data above the dolerite sill showed constant water levels (or even rising during rainfalls), whereas the data below the sill showed that pore pressures were dropping due to the impact of sub-horizontal drains installed on the pit slopes below. This clearly indicated that the top part of the dolerite sill created a perched aquifer system that could not be effectively drained by the sub-horizontal boreholes.

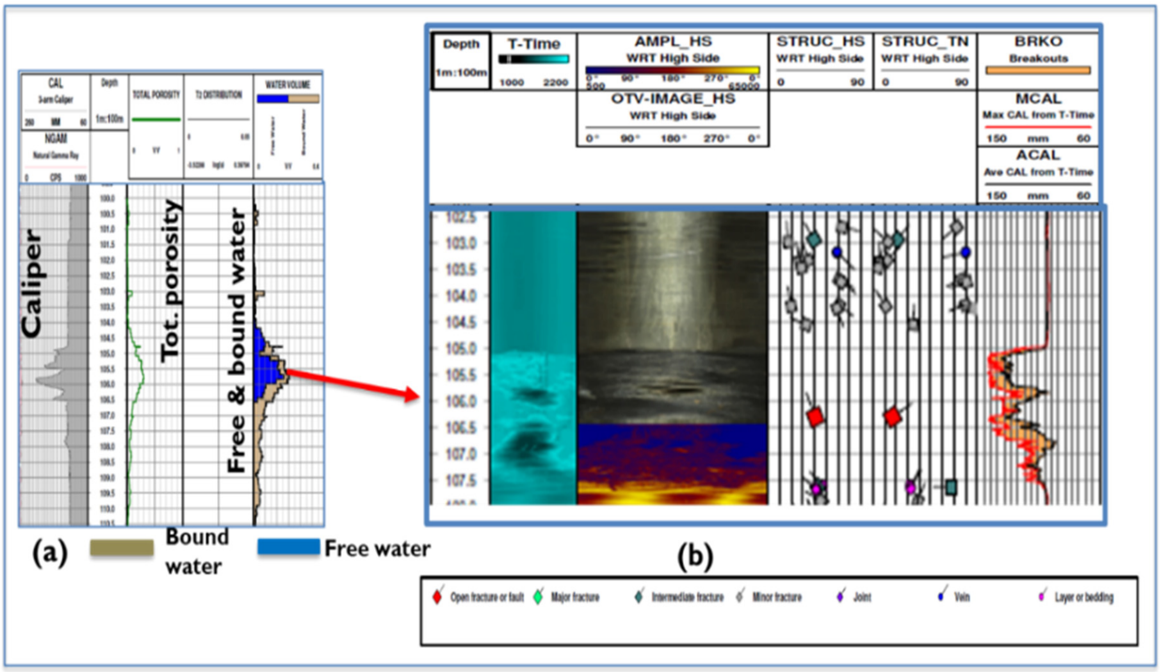


Figure 6 **(a) Free and bound water profiles down one of the boreholes at Jwaneng; (b) The same interval interpreted as an open fracture from the optical televiewer data**

The bNMR technique is used to guide placement of not only the pumping boreholes but also the sub-horizontal boreholes for passive dewatering. Figure 7 shows an example whereby high-yielding sub-horizontal boreholes were successfully drilled in the south-eastern side of the pit to target a highly permeable zone identified from bNMR data in core boreholes drilled for various mining studies. Boreholes GT 190 and 198 are collared outside the pit but inclined towards the pit slope (among the green circles in Figure 7b), whilst P79 is an in-pit drain hole at the pit bottom. A picture of the water draining out of this borehole is shown in Figure 7c.

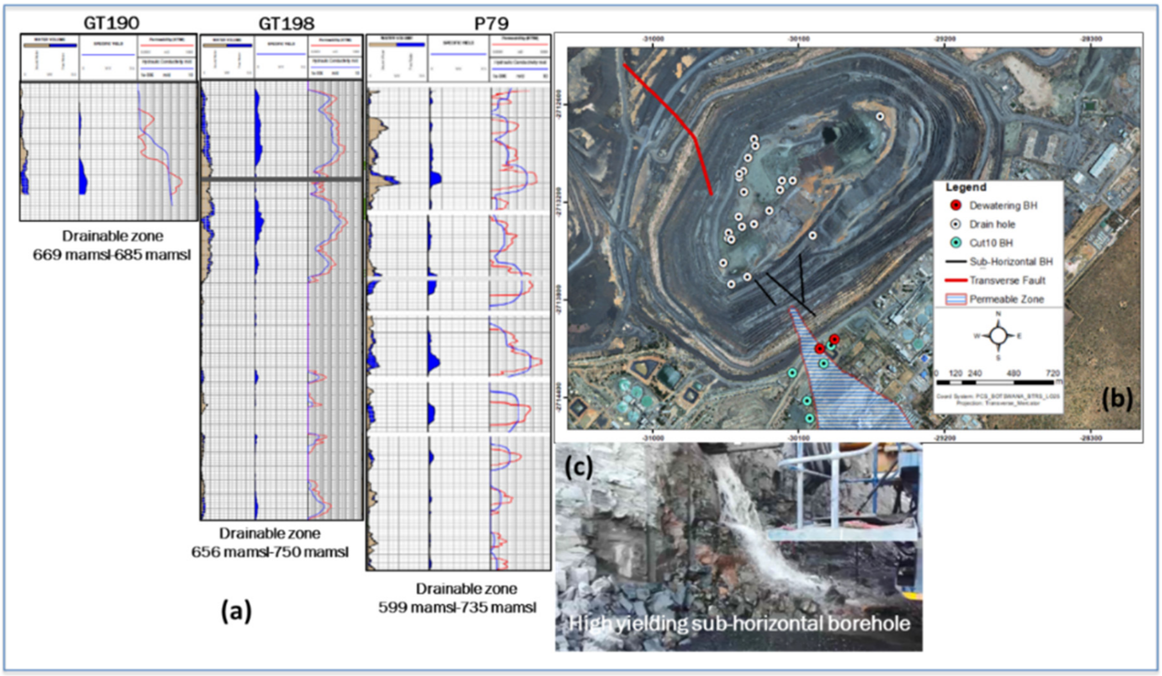


Figure 7 (a) Borehole nuclear magnetic resonance downhole data plots – blue zones indicate free water; (b) Map showing locations of sub-horizontal boreholes targeting the free water zone around 700 mamsl; (c) Picture of water gushing out of the highest yielding sub-horizontal borehole – the initial yield was in excess of 20 m^3/hr but reduced with time

5.2 Installation of variable speed drive pumping system

For effective pit dewatering, there is a need to drop the water to a target level and maintain it at that level for as long as possible. Prior to 2012, all the dewatering boreholes were operating on positive displacement (PD) pumps and these were proving to be problematic, as they required frequent maintenance – especially those on the pit crest. This was caused mainly by the snapping of the top shaft in the rising main due to vibrations caused by blasting in the pit. The inability of the PD system to adjust the pumping rate automatically as the water level reaches the target level above the pump (normally set to 5–10 m), creates a situation whereby the pump has to stop and start many times once it reaches the target level and this does not help the duty cycle of the pump – as these are hard stops and starts. The situation is different for a VSD system, as the rate is adjusted automatically to low pumping rates as the water level approaches the target water level such that it keeps on running. This avoids the frequent stops and starts and even if the pump stops, it ramps on and off softly.

6 Depressurisation performance

To assess the effectiveness of the dewatering and depressurisation, an assessment of the measured water levels from the dense VWP monitoring network was carried out by comparing the measured and simulated water levels over time, as shown in Figure 8 as an example. In this northeastern corner of the pit where modifications to the mine pit design were necessitated by potential slope instability due to unfavourable structures and bedding, additional dewatering infrastructure was developed. The hydrographs from measured water levels show the resultant drawdowns over time due to the pumping of the boreholes. Also, notice increases in heads during periods when the pumping boreholes were not in operation and/or during rainfall events. Throughout the period since the boreholes were activated, the mine has been able to maintain groundwater levels to meet the target phreatic surface, defined by the slope stability analysis, in most locations that have been monitored since 2013.

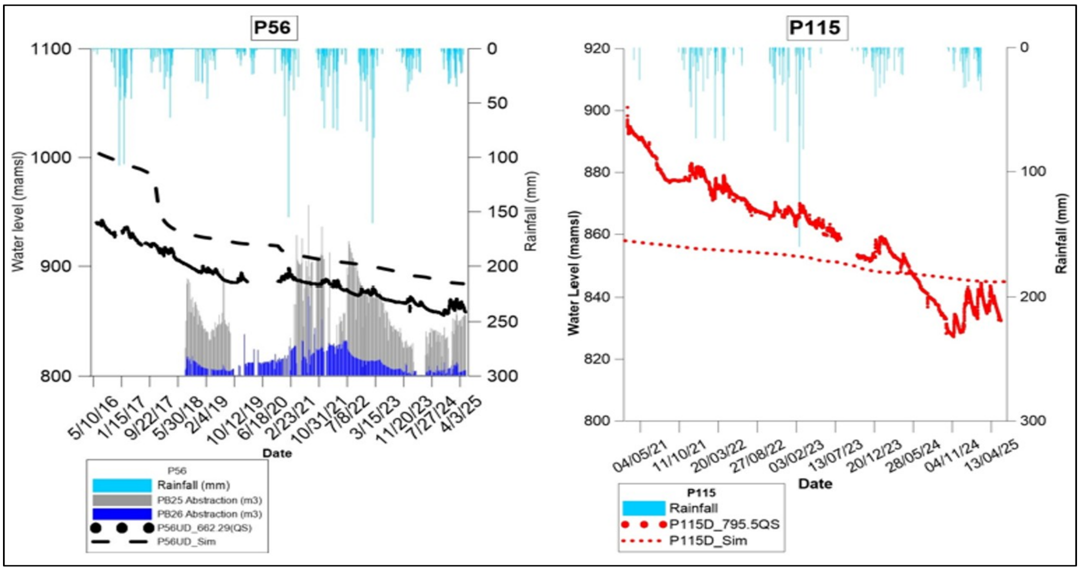


Figure 8 Time series graphs showing details of water-level performance in the northeast corner of Jwaneng Mine pit (dashed lines in both Figures refer to the target water levels)

7 Conclusion

The Jwaneng dewatering system has evolved from 5 dewatering boreholes in 2012 to the current extensive system running on 28 boreholes, 64 sub-horizontal boreholes and 71 multi-level VWPs, providing 200 pore pressure points. A robust telemetry system for both the production boreholes and piezometers allows for real-time monitoring and performance trending. The following key points have led to the successful implementation of the dewatering program at the Jwaneng Mine:

1. Support from the management team and other departments. This was especially important in the successful replacement of all PD pumps with VSD pumps.
2. Close interaction between the geotechnical group and hydrogeologic group. This interaction enabled the design of a cost-effective dewatering program to ensure the slope design meets the stability requirement. For installation of the required infrastructure, working closely with the mining team is quite critical as well.
3. Effective use of the groundwater flow model as a planning tool. The robust groundwater flow model was used as a tool for planning the future dewatering program.
4. Proactive exploration of new technology and options. Use of the bNMR technique and exploration of in-pit dewatering infrastructure enhanced the performance of the depressurisation.

Acknowledgement

The Jwaneng hydrogeology team would first and foremost like to acknowledge the critical role that the Debswana management played in giving the team the necessary support to explore technological innovations to allow for the installation of a world-class dewatering system. The continuous constructive technical critiquing of the system and guidance by the GRB spared us in pulling off a difficult feat of depressurising the pit in one of the most difficult environments of not only very low hydraulic conductivity, but complex fracture-controlled flow regimes.

The Jwaneng Mining and Engineering departments are greatly acknowledged for facilitating the installation of the dewatering infrastructure and the continuous care and maintenance of the infrastructure to allow for optimal performance. ITASCA (Denver, Colorado) played a critical role in groundwater modelling and talent development, not only at Debswana but also through a partnership with one of the local consulting companies.

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