Rockpass stability and rehabilitation at AngloGold Ashanti's Tau Lekoa Mine

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Synopsis

Scaling of rockpasses was problematic at Tau Lekoa Mine prior to production commencing in 1991. High horizontal stress levels relative to the host rock mass strength have been instrumental in causing the observed scaling. Scaling has been more pronounced in the deeper rockpasses and these are monitored regularly. Rehabilitation of one of the reef passes and one of the waste passes was required in the period 1999 to 2001. This paper describes the extent of the problems experienced to date as well as the rehabilitation completed.

Introduction

Tau Lekoa Mine is located approximately 170 km southwest of Johannesburg in the North West Province of South Africa. The mine has been in production since 1991.

A scattered mining method, using pre-developed tunnels to gain access to the reef, is employed to extract the narrow tabular orebody. The reef mined is the Ventersdorp Contact Reef (VCR). The VCR channel width varies between 0.1 m and 3.0 m in thickness and dips at approximately 30° to the west. The area is intersected by several major faults striking northeast to southwest and dipping southeast. Mining at Tau Lekoa Mine is conducted in an intermediate depth environment between 900 m and 1650 m below collar elevation.

Stress measurements conducted 1200 m below collar elevation in 1988 (Lombard, 1989) indicated the following:

- A near vertical stress of 30–40MPa
- A high horizontal stress of similar magnitude, acting north-south
- A low horizontal stress acting approximately east-west.

According to Lombard (1989) the uniaxial compressive strength (UCS) of the hangingwall lava varies between 180 MPa and 280 MPa and that of the immediate footwall between 150 MPa and 220 MPa. Work by Rosenblatt (1994) indicated average UCS values of 180 MPa, 155 MPa and 125 MPa for VCR, hangingwall lava and footwall quartzite, respectively. Several lava types have been identified and the UCS values varied between 185 MPa and 330 MPa (Fourie, 1999). Two major joint sets were identified at Tau Lekoa Mine with one set trending north-south and the other east-west. Both joint sets dip at 70–90°. The generalized stratigraphic column, indicating average UCS values, is shown in Figure 1.

The rockpass system

Levels at Tau Lekoa Mine are spaced 150 m apart vertically and are named according to the depth below collar. Ore and waste rock is transported down to the belt level (1734 m below collar) via a series of bored rockpasses extending from 900 Level down to 1650 Level, with storage silos between 1650 and 1734 Levels. The reef pass system is located between 35 m and 45 m east of the rock and ventilation (RV) shaft. The waste pass system is approximately 65 m south of the reef pass system. The rockpasses are near vertical and were bored with a diameter of 2.4 m. The exceptions are the 1500–1650 rockpasses that have average inclinations of 80° to the east. The rockpasses are connected via tapping passes. The shaft and rockpass systems are situated in an oval shaft pillar, which has a maximum length of 475 m and width of 400 m.

The rockpasses between 900 and 1050 Levels are sited in lava and those between 1050 and 1200 levels in the Denny's quartzite. The lower level passes between 1200 and 1734 Levels, inclusive of the silos, are sited in Main Bird quartzites (MB 8–10).

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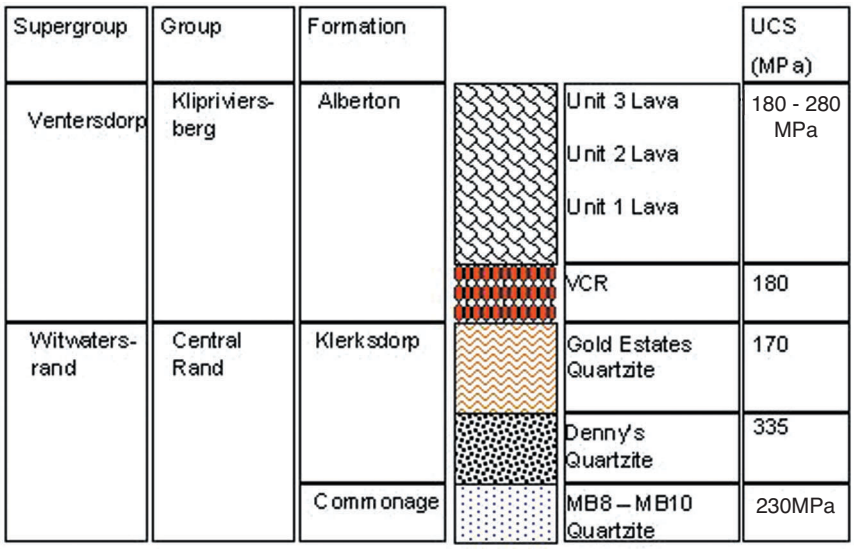


Figure 1—The generalized stratigraphic column indicating the average UCS (Dunn and van Oort, 2002)

Table I

Extent of scaling (m) in rockpasses

Excavation	Vertical extent below level	Extent to the west	Extent to the east	Total E-W extent	Extent to the north	Extent to the south	Total N-S extent
1050–1200 Waste pass	15	0.89	1.16	2.05	0.79	1.45	2.14
1050–1200 Reef pass	15	1.81	1.36	3.17	1.31	1.35	2.76
1200–1350 Waste pass	40	0.73	2.32	3.05	1.23	1.66	2.89
1200–1350 Reef pass	53	1.68	3.87	5.55	1.31	1.35	2.66
1350–1500 Waste pass	120	4.30	4.10	8.40	1.60	2.50	4.10
1350–1500 Reef pass	50	2.20	5.40	7.60	2.90	0.90	3.80
1500–1650 Waste pass	80	5.00	8.50	13.50	2.30	8.40	10.70
1500–1650 Reef pass	80	4.60	5.00	9.60	1.00	4.50	5.50
1650–1734 Reef silo	50	9.30	18.20	27.50	4.10	5.50	9.60
1650–1734 Waste silo	35	15.30	6.80	22.10	3.10	6.70	9.90

Rockpass scaling

Scaling of the rockpasses started early during the life of the mine and was first observed in the rockpass connecting 1050 Level to 1200 Level some two months after it was bored (Devine and Palmer, 1992). Deterioration in terms of scaling of the rockpasses between 1500 and 1734 Levels, including the silos, became especially evident over the last few years. This dictated the need for rehabilitation, which was prioritized and phased in.

Annual examinations, and plotting the observed extent of scaling, have been practised in these passes. Some observations have been conducted on the upper levels (900 to 1350 levels), but not as regularly, since the rockpasses below are considered more problematic. Table I shows the extent of the scaling and direction of scaling in the waste and reef passes. Figure 2 shows the position of the RV Shaft barrel and the rockpasses on 1500 and 1650 levels with an indication of the extent and direction of the scaling.

Theoretical understanding of rockpass scaling

The scaling observed in the Tau Lekoa Mine rockpasses is typical 'dog-earing' as observed around a circular borehole or circular excavation occurring at all scales. Dog-earing occurs in an anisotropic stress field as a result of stress concentrations at points on the pass wall situated perpendicular to the major principal stress axis (Figure 3).

In the case of rockpasses (steeply dipping circular holes), considerable work has been done on the theory of stability. Important parameters include the magnitudes and orientations of the three principal stresses, the orientation of the circular hole with respect to the principal stress axes, the presence or absence of internal pressure acting on the circumference of the hole and the strength of the strata through which the hole passes.

Generally rock begins to fracture at stress levels equal to about one third of the UCS. Figure 4 shows the stress distribution around a circular hole in a biaxial stress field (stress ratio k = 0.25). The tangential stress at the boundary is 2.75 q (q = virgin stress) at the side and –0.25 q at the top. The tangential stresses drop to the virgin stress level at about three times the radius at the side (Budavari, 1983).

The radial stress at the side is zero at the boundary, increasing to –0.5 q and then tending towards the virgin stress with distance away from the excavation boundary. At the top the radial stress tends towards the virgin stress at

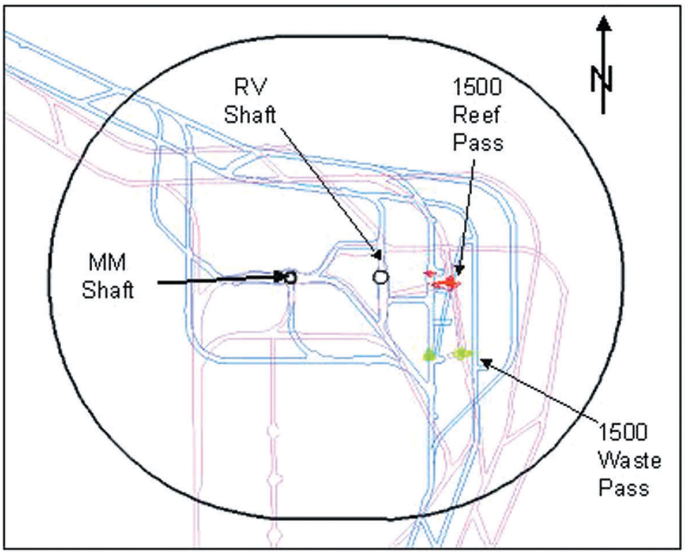


Figure 2—Plan showing the position of the RV shaft barrel and the rockpasses on 1500 and 1650 levels with an indication of the extent and direction of the scaling

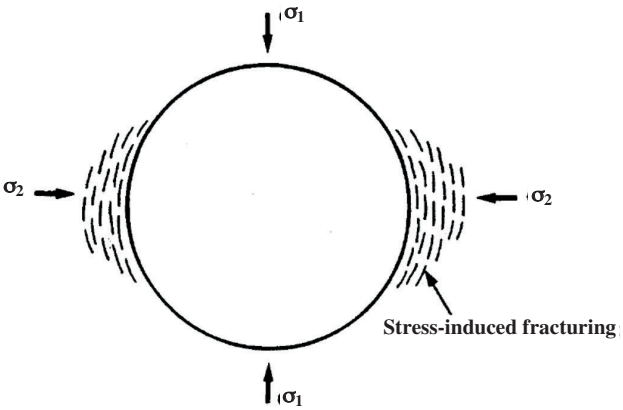


Figure 3—Stress-induced fracturing around a tunnel in an anisotropic stress field (after Budavari, 1983)

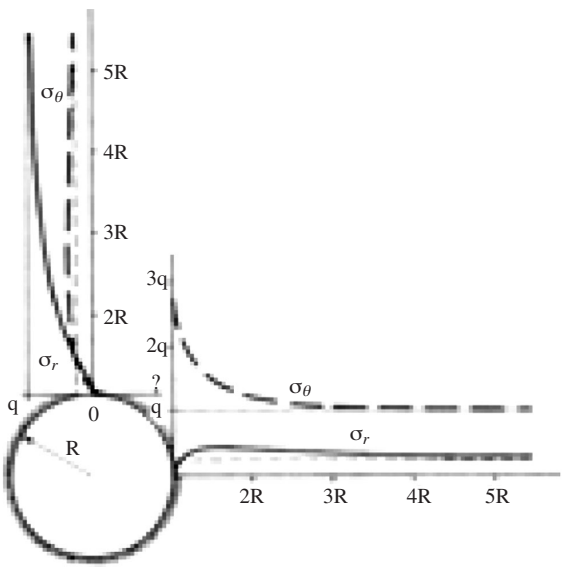


Figure 4. Distribution of stresses around a circular hole under biaxial loading, k = 0.25 (after Budavari, 1983)

about five times the radius away from the boundary. This concentration of stress at the sides of the tunnel results in fracturing and progressive scaling until a degree of stability is achieved some distance away from the boundary of the circular excavation.

With respect to the *in situ* state of stress, the important parameter is the difference in magnitudes between the principal horizontal stresses. If there is a significant difference between the two stresses, failure of the hole is likely at two diametrically opposite points where the tangential compressive stresses are the greatest. As a result of this failure, the cross-section of the hole tends to become elliptical with the long axis parallel to the least compressive secondary principal stress. Generally the maximum principal stress is close to vertical. The likelihood of failure of the hole in this manner is clearly a function of the strength of the rock strata through which the hole passes. In general, there exists a marked horizontal stress anisotropy in the major South African goldfields. Therefore, rockpasses should be expected to fail should the stress concentration acting on the pass be sufficient to exceed the compressive stress of the strata and initiate failure of the rockpass (Gay, 1992).

Risk assessment

The risk associated with the shaft infrastructure is largely based on observations and is thus qualitative. An attempt has been made to quantify the risks, but this is hampered by the lack of data and various assumptions have been made. The approach adopted is described by Dunn and Menzies (2005) and will therefore not be repeated here. This method attempts to quantify the risk using a matrix in which two parameters, namely damage severity and interaction risk, are plotted and from which the rockpass risk potential is determined.

The results of the risk assessments conducted on the waste and reef pass systems are shown in Tables II and III.

Table II

Waste pass system risk assessment

(i) Waste pass	(ii) Information reliability	(iii) Interaction status	(iv) Interaction risk	(v) Damage status	(iii) Risk potential	Comments
900–1050	3	1	3	3	B	**
1050–1200	3	1	3	3	B	**
1200–1350	3	1	3	3	B	**
1350–1500	3	1	3	3	B	
1500–1650	3	1	3	4	AA*	
1650–1734	3	1	3	3	B	Original diameter 8 m

**Dimensions based on 1350–1500
The risk potential ratings are defined as follows:
AAA — Disaster scenario imminent
AA — Disaster scenario developing
AA* — Damage unlikely to be due to interaction, look for other causes
A — Possible production delays
B — Low likelihood of delays
C — Negligible likelihood of delays

Table III

Reef pass system risk assessment

(i) Reef Pass	(ii) Information Reliability	(iii) Interaction Status	(iv) Interaction Risk	(v) Damage Status	(iii) Risk Potential	Comments
900–1050	3	2	6	3	B	**
1050–1200	3	2	6	3	B	**
1200–1350	3	1	6	3	B	**
1350–1500	3	2	6	3	B	
1500–1650	3	2	6	4	AA*	
1650–1734	3	2	6	3	B	Original diameter 8 m

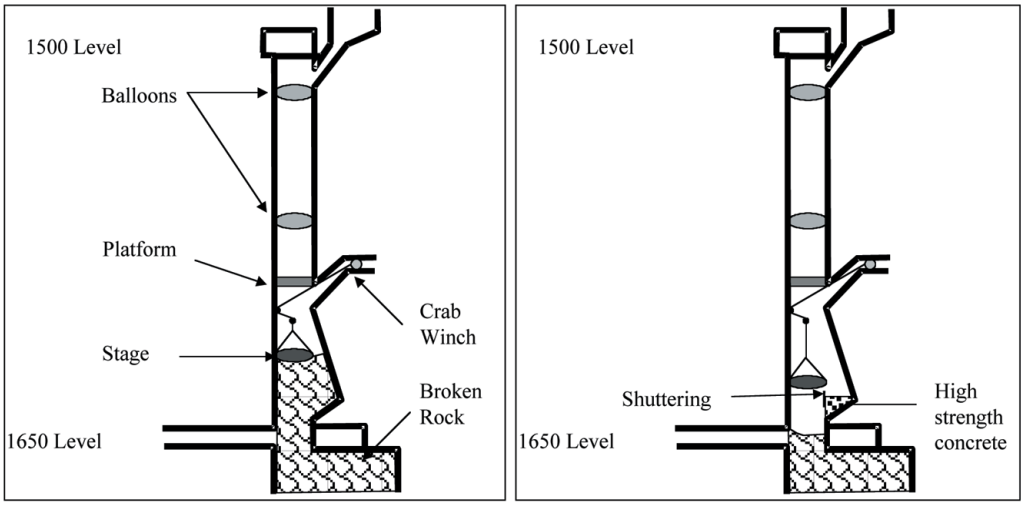
**Dimensions based on 1350–1500

Rehabilitation

1500 to 1650 reef pass rehabilitation

Any rehabilitation to a rockpass can be classified as a time-consuming, high-risk operation. Detailed planning was required, not only to minimize downtime, which obviously impacts on production, but to deliver a cost effective product to the required standard. Extended breaks over the festive period were considered the perfect time slots for this work. December 1999 was the start of the process with the rehabilitation of the western sidewall, followed by the eastern sidewall in December 2000. As rockpass rehabilitation is a specialized operation, contractors were used to carry out the work. The process followed in 2000 is described below:

- The reef pass was filled with broken rock up to the connecting incline between the waste pass and the balancing cross-cut. The connecting incline intersection with the reef pass coincided with the upper boundary of the scaling
- A 'balloon' was lowered into the reef pass to a position approximately 120 m below 1500 Level. The 'balloon' consisted of a bladder made from the type of material used in the manufacture of inflatable boats. A net constructed of nylon rope surrounded the bladder. The balloon was connected to an air hose and lowered to the required position where it was inflated. The inflation principle used is similar to that of a jumping castle—air is constantly pumped into the balloon while at the same time being released
- A second balloon was then installed approximately 40 m below 1500 Level (Figures 5 and 6).
- Working from the broken rock, a platform was constructed across the diameter of the reef pass to serve as a canopy to protect workers below
- A crab winch was erected in the balancing cross-cut and rigging arrangements for the stage installed in the rockpass sidewalls. The stage consisted of a steel platform manufactured in two halves and bolted together in the rockpass. The stage was suspended from the crab winch and provided a working platform that, after the initial erection, obviated the need for people to stand on the broken rock
- Rock was then drawn from the rockpass and the level of the rock in the waste pass lowered by 5 m. The change in the level of the ore in the reef pass was compared to the volume of rock drawn at the bottom to ensure that no voids were created in the ore filling the pass. Chain ladders were installed from the connecting incline and extended as work progressed down the rockpass. The sidewalls were made safe and supported with 1.8 m long steel bars. This process was repeated until the stage reached 1650 Level, where the rehabilitation process stopped
- A 100 mm pipe with a 'kickback' was installed against the rockpass sidewalls and timber shuttering installed to allow a continuous cast and lift. A 'kickback' is a near-horizontal portion of the shutter onto which the bottom batch of concrete is poured. To assist in the



Figures 5 and 6—Sections through the rockpass illustrating the main components of the rehabilitation process

installation of welded mesh against the concrete fill, wire was installed through the shuttering, into the void to be filled by the concrete

- High strength concrete was mixed in the balancing cross-cut and piped to the void behind the shuttering. The concrete had a 7-day strength of 40 MPa and a 28-day strength of 60 MPa. Eyebolts were installed at 500 mm intervals in a horizontal ring at the top of the rehabilitation sector. 14 mm link chain was suspended from the eyebolts, behind the shuttering, to form a chain barricade to provide additional reinforcement of the concrete. The shuttering was continually extended as the concrete was poured
- As the shuttering was removed, 50 mm by 50 mm aperture weldmesh sheets were attached to the newly cast concrete and shotcrete sprayed over the weldmesh to a minimum thickness of 300 mm. The shotcrete used contained corundum aggregate and had a 6-hour strength of 35 MPa and a 28-day strength of 90 MPa
- Installation of shuttering, casting of the concrete, removal of the shuttering and attachment of the weldmesh were able to take place simultaneously in different sections of the pass because of the stage that was used
- On completion of a section of the shotcrete, water was sprayed onto the shotcrete to ensure proper curing
- Great care was taken to catch the rebound and thus prevent the rockpass from hanging up after completion of the rehabilitation project.

1500 to 1650 waste pass rehabilitation

During 2001, a holing of less than 1 m^2 occurred between the waste pass and the 1500 tipping haulage. Further investigation revealed substantial scaling and undermining of the tip area with the loss of a reinforcing/supporting wall. Rehabilitation was then planned for the Christmas break.

A similar procedure was followed to rehabilitate the waste pass except that, since only approximately 12 m of the rockpass required rehabilitation, a platform and crab winch were not used.

Discussion

Rockpass scaling

Many of the factors identified by Gay (1992) as being contributors to rockpass scaling are present at Tau Lekoa Mine and are briefly discussed below.

- *Geology*—According to Devine and Palmer (1992) the rockpass system at Tau Lekoa Mine has been developed in a structurally complex zone, which would contribute to scaling. Well-developed bedding planes that occur in the Gold Estates quartzites and the MB 8-

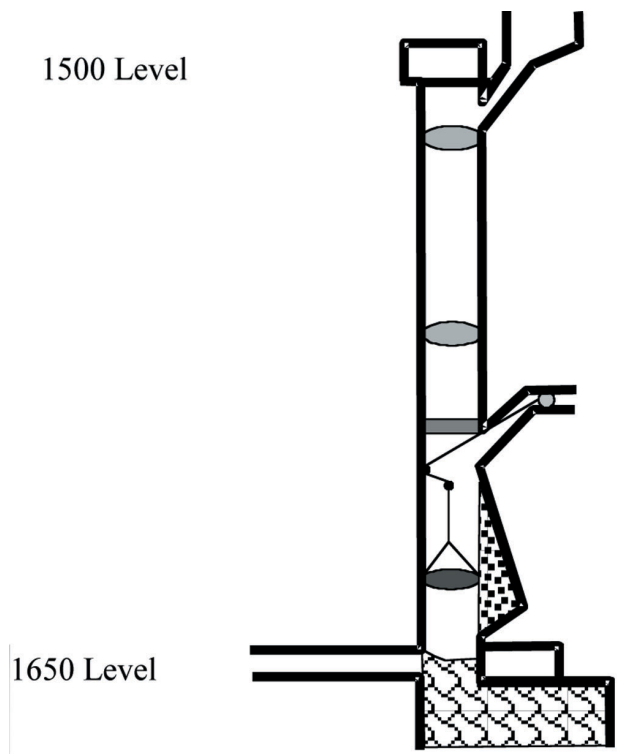


Figure 7—Section illustrating the rehabilitated rockpass

10 quartzites, and jointing within the Klipriviersberg lavas, would aggravate the problem further. The 1650 reef silo is situated partially in dyke with several small faults in close proximity. Several of the rockpasses are intersected by faults.

- *Horizontal stress difference*—There are significant differences between the horizontal stress components, with a high horizontal stress in the north-south direction (k = 0.8) and a low horizontal stress in the east-west direction (k = 0.15). This difference is the major contributor to the dog-earing in the east-west direction.
- *Depth and stress levels*—At the Tau Lekoa Mine depths, the virgin stress levels and stress concentrations on the circumference of a circular excavation are sufficient to cause fracturing of the rock. Indications are that the degree of scaling increases with depth. The extent of scaling is greater on the lower levels.
- *Impact and abrasion*—The long rockpass legs (150 m) result in substantial impacts and abrasion at points of weakness such as the footwall and where rockpasses intersect each other.
- *Interactions of excavation*—Interaction between the rockpasses, tipping haulages and tapping passes result in increased localized stress and a greater degree of fracturing, contributing to increased scaling.

Risk assessment

The methodology applied provides a consistent approach to quantifying the risk associated with rockpasses based on empirical rock engineering guidelines.

A major weakness with the methodology is that potentially damaging seismic events are not considered. A second limitation is not directly related to the methodology, but to the difficulty in obtaining accurate rockpass dimensions. These are currently obtained by suspending personnel in the rockpasses from ropes, and measurements are, at best, good estimates.

Monitoring and rehabilitation

Regular monitoring of all rockpasses on Tau Lekoa Mine reduces the risk substantially and allows rehabilitation work to be planned and conducted before major problems are experienced. By taking regular measurements, the progression of scaling can be plotted and monitored.

Observations in the 1500 to 1650 Level reef pass, following rehabilitation, show that scaling is starting in a north-south direction. This is due to the weakness of the rock relative to the corundum shotcrete. A small likelihood exists that the reef and waste passes could hole into each other if scaling in the north-south direction is left unchecked. A corundum shotcrete lining over the full circumference of the reef pass could prevent this.

A possible solution to the impact problem would be to reduce the length of the legs by installing plugs and developing tapping passes. However, the introduction of additional excavations could also exacerbate the problem.

Due to production constraints and the absence of a third rockpass system, critical maintenance and rehabilitation of the rockpasses can be carried out only over extended breaks. During these breaks only a portion of the time may be available for rehabilitation within the rockpasses.

Detailed planning and preparation was critical to the success of the rehabilitation projects. This enabled the work not only to be completed during the Christmas breaks, but up to two days ahead of schedule.

Conclusions

The main contributor to rockpass scaling at Tau Lekoa Mine is the relatively high horizontal stress in the north-south direction and the low stress in the east-west direction. Other factors such as geology, rock mass competency and layout also contribute.

The rockpasses below 1500 Level are regarded as having a higher risk than those above 1500 Level based on observations to date. The main risks associated with the rockpasses are:

- Dilution in the reef passes
- Loss of tip areas down a reef pass on 1500 and 1650 Level
- Possible holing between the reef and waste passes
- Possible damage to the shaft.

The stability of the tipping haulages is a cause for concern and should be regarded as medium to high risk; further investigation is required. The condition of tip area foundations is extremely important and must be regularly monitored and rehabilitated when necessary.

The risk associated with the Tau Lekoa Mine rockpass system must be actively managed to ensure that the mine remains financially viable.

The rehabilitation work completed in the 1500 to 1650 Level rockpasses to date has been successful.

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