Orepass best practices at South Deep

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Synopsis

After the South Deep complex was purchased by Goldfields in 2006 a re-feasibility study was done and the life of mine (LOM) was extended to 52 years. This also implied that the mine's infrastructure would have to be enhanced. One of the changes was the proposal of five new main orepass systems to be excavated before the mine reaches full production in 2013. Excavations started to show signs of scaling, and in some cases, whole new excavations were lost. This particular area was exposed to very high stresses and the geology was prone to body delimination rendering the relevant areas unstable. This paper investigates the conditions at the location of one of the proposed orepass systems, and the best possible orientation was suggested to ensure that the orepass system would be stable and have a practical life. It was, however, found that the fourth leg of the orepass system would require further support to be classified as stable by the chief rock engineer and the section geologist of South Deep. Several support methods and orepass system linings would then be analysed and evaluated to give calculated recommendations on how to productively and practically support an orepass system.

Keywords

Main orepass system, stresses, body delamination, impact and abrasion, rock support, concrete lining.

Introduction

This paper contains basic information about South Deep and the project objectives and methodology.

Mine background and general information

South Deep was purchased in 2006 by Goldfields and a full re-feasibility study was done on the mine. The life of mine (LOM) was determined as 52 years. The mine is situated in the West Rand, Gauteng as seen in Figure 1. South Deep Gold Mine is an intermediate to deep level gold mine with various auriferous conglomerates that occur at depths between 1 575 m and 3 500 m below surface. There are two shaft systems, comprising the older South Shaft complex with its main shaft and two sub-vertical shafts, and the latest system known as Twin Shafts.

South Deep is currently producing approximately 360 000 ounces of gold per annum. In 2012, gold production is planned to increase to 750 000 ounces per annum.

Overview of Twin shaft and main orepass system layout

Figure 2 shows an overview of the development (current and proposed) in the bottom section of the Twin Shafts system. The operational main orepass systems are currently responsible for transporting all the broken rock to the shaft bottom. One pass system is dedicated to ore, and the other one to waste. These main orepass systems have sufficient capacity at present; however, they cannot handle the capacity once the mine reaches its planned full production in 2012. It is therefore proposed to excavate five new main orepass systems to handle the build-up in production. One of these main orepass systems would be situated next to the current two main orepass systems and the other four on the opposite side of the shafts, as indicated in Figure 2. This paper will focus on the proposed main orepass system next to the current two main orepass systems as it is scheduled to be developed before the other four.

This main orepass system is proposed to comprise four legs:

- ➤ The first leg from 95–100 level,
- ➤ The second leg from 100–105 level,
- ➤ The third from 105–110 level
- ➤ The fourth leg from 110–110A level.

Geology

The reef horizons exploited by Goldfields at South Deep include the Ventersdorp Contact Reef (VCR) and the stacked reef horizons that comprise the Upper Elsburgs as seen in the indicated area on the stratografic column in

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Figure 1—Location of South Deep, Twin Shafts

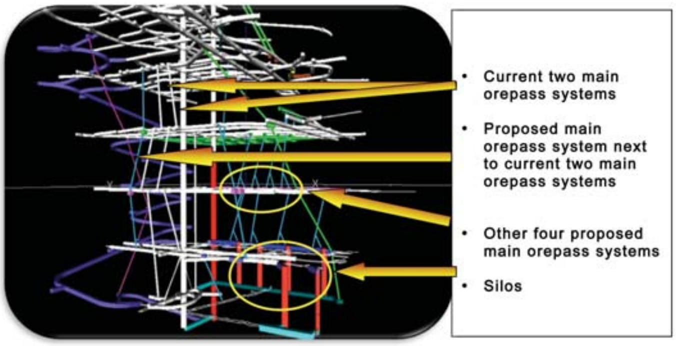

Figure 2—Overview of South Deep, Twin Shafts

Appendix B. The primary economic target is the Upper Elsburg reef package dipping 12° south-southeast with the VCR being a secondary economic target. The VCR strikes roughly east-west and has a regional dip of approximately 15°.

Mining methods

South Deep is a fully mechanized operation divided into two main phases, namely de-stressing and main production. De-stressing by is done by mining a 2 m slice in an optimal position to ensure a de-stressed window of 50 to 60 m above or below the associated stope. Untill the middle of 2008, this was done through conventional longwall mining techniques, but was changed to a mechanized technique due to the increased face advanced.

Main production at Twin Shaft is done by a variety of mining methods ranging from mechanized drift-and-fill or modified drift-and-bench to longhole stoping Basically, the ore would be drilled with trackless twin boom drilling rigs, blasted and taken by load haul dumpers (LHDs) to the main orepass systems where it would be transported to shaft bottom and then hoisted to surface.

Definition of an main orepass systems

According to West Somerset Mineral Railway, an orepass is defined as, ‘a vertical or sub-vertical connection between stoping levels and/or sub-levels of mines. Such passes are for the transfer of ore only’. This paper deals with main orepass systems; these are connections between levels of the mine, used to transport ore as well as waste from the different levels to shaft bottom, where the ore is hoisted to surface to be processed in the mineral processing plant.

Problem statement

A main orepass system would not only be exposed to the high stresses and the areas of fragile geology present at the Twin Shaft of South Deep Gold Mine, but it would also be subject to impact and abrasion, and the combination of these conditions could lead to the collapse or self-mining of an main orepass system. If the mine should mislay the use of their current main orepass system it would create a bottleneck in production due to the ore being unable to be hoisted out from underground. The mine would not be able to transport the ore or waste rock out of the different levels to

Table I

Objective and methodology

Objective	Methodology
Develop an understanding of the problem statement and the factors influencing it.	Do a literature survey on factors that cause orepasses to fail.
Determine possible mode of failure of the current orepass system.	Study the relevant geology and stresses.
Evaluate and analyse the results obtained.	Use information obtained during investigation and identify problem areas relative to specific parameters. Identify possible solutions and determine their feasibility.
Draw conclusions and recommendations from the investigation.	Recommend viable methods or procedures to effectively align and support orepasses.

shaft bottom, where it would be hoisted out of the mine. In addition, the plant could be compromised if there is no ore to be processed. Finally, excluding the cost of refurbishments to the orepass system, the mine would lose approximately 33 000 ounces of gold per month. The current gold price of R1 150 per ounce and the R/$ exchange of R7.36 (2010-04-27) the mine would lose R280 million per month. This monetary value justifies the mine's investment in resources to ensure a stable, long-term orepass system.

Objectives and methodology

See Table I.

Scope of the study

A literature study on current best practices of main orepass systems in ultra deep mines was done and several key parameters on the design and operation were identified. The final leg of the one proposed main orepass system was analysed. This part of the orepass system was considered critical due to very high stresses and weak rock conditions through which it is planned to be excavated. Conclusions were drawn through the analysis of the results obtained and recommendations were made.

Literature survey

In this section literature of past failures of orepass systems will be analysed, and relevant variables established to better understand the process of designing and operating successful orepass systems.

Design considerations

From the available sources eight key design parameters were identified in the successful design and operation of an ultra deep long-term orepass system. These will be discussed and explained in the following section.

Geology

Gay (1992:134) reports that geology is one of the biggest factors that influence the stability of orepass systems. The geological factors are: rock strength, tectonic structures and the internal structure of the rock. Rock strength is the most important factor. Rech, Otto And Hagan () agree with Gay and adds that not only weak, but layered weak rock, is the main cause of scaling (bedding delamination) of orepass systems in mines. The mode of failure is believed to be gravity pulling the strata apart. Keeping that in mind, logic dictates that when the orepass system is orientated perpendicular to or at as high an angle as possible to the strata, that the layers of rock would not be able to break away from the upper layers. In Figure 3 this concept is explained. In frame A, the excavation is parallel with the stata, so gravity breaks the strata layers apart (bedding delaminating). And in frame B, the, the excavation is perpendicular relative to the strata, rendering body delimitation kinematically inadmissible.

Stresses

Rock at depth is subjected to high stresses, and any development could consequently fail either in compression or due to shear along planes of weakness.

When a body of rock is analysed, an infinite number of stresses in an infinite number of directions can be analysed. They represented in nine different shear and normal forces as shown in Figure 4. Tau with the subscripts 11, 22, 33 represents the normal stresses, and Tau with the subscripts 12, 13, 21, 23, 31, 32 represent the shear stresses.

If the measuring axis is rotated so that all the shear stresses are equal to zero, then normal stresses would be at a maximum. These are known as the principal stresses and are what cause rock failures.

The principal forces are also represented by the Greek letter sigma (σ). The three principal stresses are: the major, intermediate and minor principal stress. The major is the largest, intermediate the second largest, and the minor the smallest principal stress. Generally, the major principal stress is vertical and is represented by σ_1. Then the intermediate and minor stress would be represented by σ_2 and σ_3 respectively; this is represented by Figure 4.

It must, however, be noted that according to Gay (1992), the principal stresses can differ with orientation due to several reasons such as de-stressing. Gay (1992) recommends that orepass systems should be developed in the same direction, or dipping as close as possible to the major principal stress to eliminate or minimize the effects of the

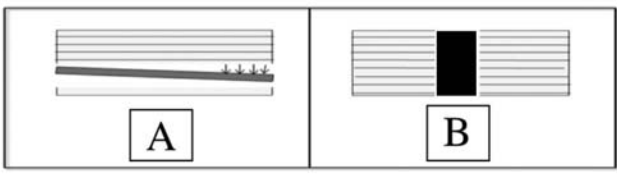

Figure 3—Kinematical admissibility

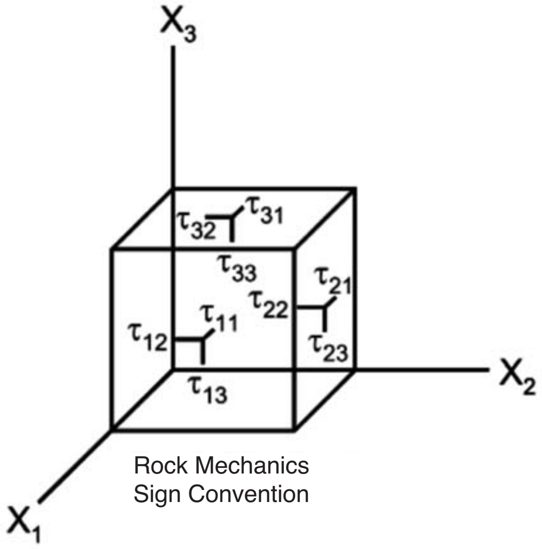

Figure 4—Illustration of stresses

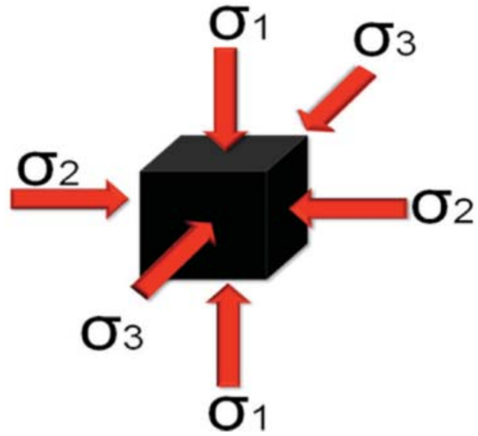

Figure 5—Principal stresses

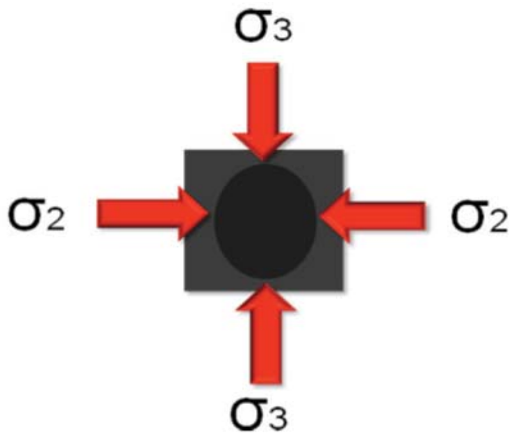

Figure 6—Plan view of intermediate and minor stress

Figure 7—Example of 'dog earing' (PSZ 411, (2010))

principal stress on the orepass system. σ_2 and σ_3 generally act on the horizontal plane onto the sides of the orepass of an orepass system, as shown in Figure 5. σ_2 and σ_3 are not equal in magnitude and act on the same plane in perpendicular directions; this causes the phenomenon known as 'dog earing'. This occurs when the intermediate stress crushes the edges perpendicular to its direction (which is the same direction as the minor principal stress, and the plane on which it acts), creating a larger area distributing the stress over a greater area concluding in equilibrium in the stress field in this plane. This implies that if a hypothetical orepass system would be developed in this oval shape, it would not deform as shown in Figure 6 because the stress field would already be in equilibrium.

Gay (1992) recommends that orepass systems developed in ultra deep mines should be developed in de-stressed areas because the virgin rock stresses are extremely high. De-stressing means mining out a portion of the mine, thereby diverting the stresses away from areas above and below this de-stress horizon, as illustrated in Figure 7.

Mechanism of wear on orepass systems

Orepass systems are special excavations in the sense that not only stresses and geolotechnical conditions can damage them, but they are also exposed to wear caused by impact and abrasion from the broken rock transported through them. Not all of the broken rock slides down the orepass system causing scouring due to friction, but a considerable percentage also bounce up and down in the orepass chipping the sides on impact, as illustrated in Figure 9.

Size of orepass

According to Aytaman (1960) the diameter of an orepass system should be at least 3 times the diameter of the largest expected rock to pass through the orepass system to prevent 'hang-ups'. If the orepass system is 5 times the diameter of the largest expected rock to pass through, it can be said with certainty that 'hang-ups' would not be caused by the wedging of rocks against one another.

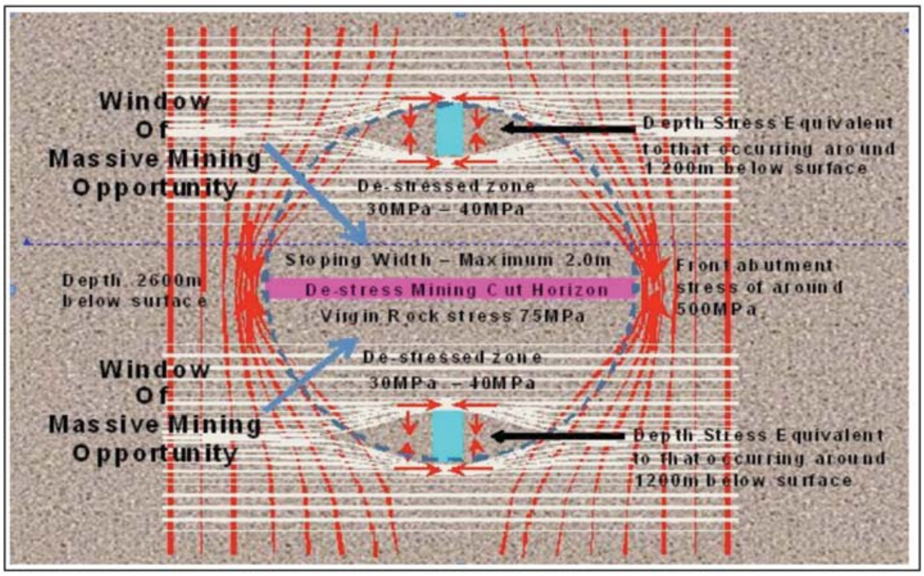

Figure 8—Example of affects of de-stressing

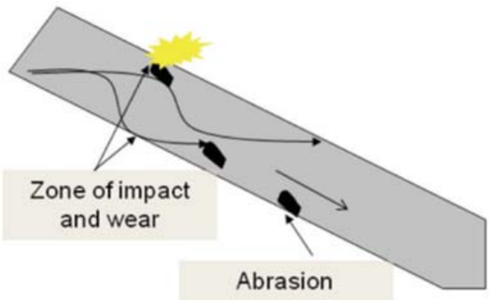

Figure 9—Mechanism of wear on orepass systems

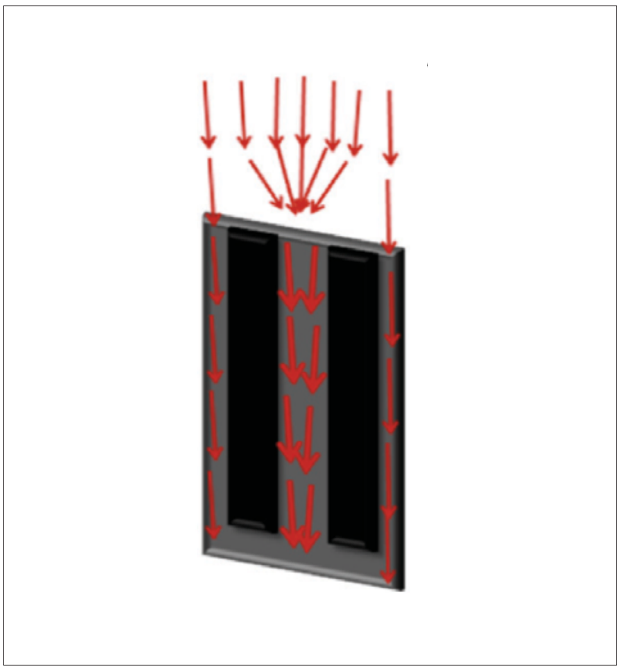

Figure 10—Representation of how stresses reacts around developments

Proximity of orepass systems relative to other excavations

It is important to consider other excavations when deciding on the location of any development because, as represented by Figure 10, the stresses (represented by the red arrows) concentrate in the pillar of rock between the two excavations. Damage to the pillar could lead to failure of the pillar. Gay (1992:137) suggests a distance not less than three times the combined diameters of the developments to ensure that the rock in between the two will not fail.

Inclination and length of a leg of a main orepass system

Momentum build-up is an important factor in both the length and inclination of any leg of any main orepass system. A leg of a main orepass system must be long enough to connect two levels. It should not be a vertical development because the momentum build-up would be too great and could compromise the safety of the people in the mine.

This is why it is suggested by Beus, Iverson and Stewart (1997) to develop a leg of an orepass system between 60°–70° to maximize rock flow and minimize momentum build-up of the broken rock. Also, due to momentum build-up and complications to treat hang-ups, a leg of a main orepass system should ideally not exceed 45 m. The length is also a function of the proposed angle to which the orepass system is to be excavated. In Table II the maximum length of a leg of a orepass system to different angles can be seen.

What is known as a dog-leg is excavated in another direction at the bottom part of the leg of the orepass system, as seen in Figure 11. The impact of broken rock due to the momentum build-up is absorbed in the impact zone, as seen in Figure 11. This zone gets worn out over time and small rocks fill this void which absorbs the impact. Once the impact zone is covered with these impact-absorbing rocks, it is referred to as a 'dead box' because it absorbs most of the momentum of the rock flowing in the orepass. At the dead box, the broken rock is then deflected down the dog-leg to the next level. Figure 11 shows an example of a dog-leg. (Aytaman, 1960)

Table II

The maximum length of a leg of a orepass. (Murray and Robberts)

Angle	Length	Angle	Length	Angle	Length
45°	15	55°	27	65°	32
46°	17	56°	28	66°	33
47°	19	57°	28	67°	33
48°	21	58°	29	68°	34
49°	23	59°	29	69°	34
50°	25	60°	30	70°	35
51°	25	61°	30	75°	40
52°	26	62°	31	80°	40
53°	26	63°	31	90°	45
54°	27	64°	32		

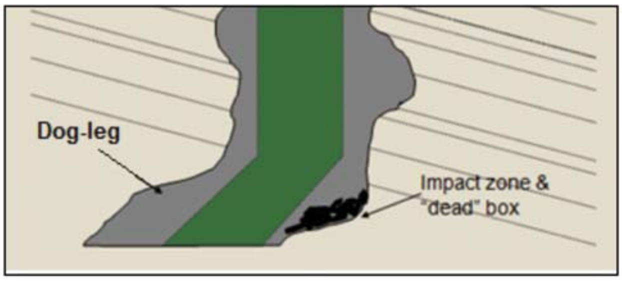

Figure 11—Dog-leg showing dead box

Support

All orepass systems are exposed to impact and abrasion. Shotcrete lining has been used with great success in the mining industry to protect the orepass systems against impact and abrasion. In weak, fissile, scaling and closely jointed rock, a lining may be the only suitable support method. Special types of lining have been used to contest the effects of orepass wear. (Stacey, 2001). To maximize the impact and abrasion resistance of concrete liners, technical literature and field experience underlined the key importance the following parameters that:

- The cement type: two main types of cement is widely used in the concrete lining of orepass systems namely calcium aluminates cement (CAC) and ordinary Portland cement (OPC). Tests carried out at a company called Lafarge Aluminates, now known as Kerneos, made it apparent that a CAC paste exhibits much better performance than a similar OPC paste when submitted to abrasion. The proposed explanation is that CAC clinker is a much harder material than OPC clinker, and thus CAC cement particles are more resistant to abrasion. In the data published by Van Heerden (2004) CAC based concrete is 13.7% more expensive that a similar OPC based concrete. This can, however, be justified by the longer expected life of CAC based cement. According to Van Heerden, CAC based concrete will outperform the life expectancy of OPC based concrete by a factor of at least 2 and up 3.5. (Fryda, 2004)
- The aggregate type and size: the selected aggregate in the mix of the concrete is the most significant factor of the liner to resist impact and abrasion. For friction abrasion, the higher the aggregate hardness, the better the concrete resistance. The best abrasion resistance was obtained with natural Corundum with a maximum diameter (D_{max}) =20 mm due to its high hardness value of 9 on the Mohs hardness scale, but the supply of Corundum in South Africa is no longer available. Thus crushed Andisite with a D_{max} =20 mm and a hardness of 6.5 on the Mohs hardness scale is the best alternative used (Fryda, 2004).
- The fibre type: fibres in the concrete mix contribute in two ways: firstly they absorb and dissipate energy, reducing crack initiation and propagation, and secondly they can maintain a fractured piece of concrete within the main body, slowing down the deterioration process (Fryda, 2004).
- The mechanical strength: according to Fryda (2006), the compressive strength of the lining does not affect the ability of the concrete to resist impact and abrasion. But there is, however, a general relationship between impact and abrasion resistance and compressive strength: the higher the compressive strength, the higher the resistance to impact and abraision. But this is very marginal if the compressive strength starts to exceed 70 Mpa, as seen in Figure 12 (Fryda, 2004)

Usually, orepass systems does not require further support. But with the increase in depth the requirement for support will depend on the following;

- Geotechnical factors: rock mass quality, geological structure, *in situ* stresses, stress changes, rock material strength
- Construction factors: method of excavation, size, shape, and inclination
- Planning factors: desired life, tonnage to be handled, strategic importance, time between excavation and usage (Stacey, 2001).

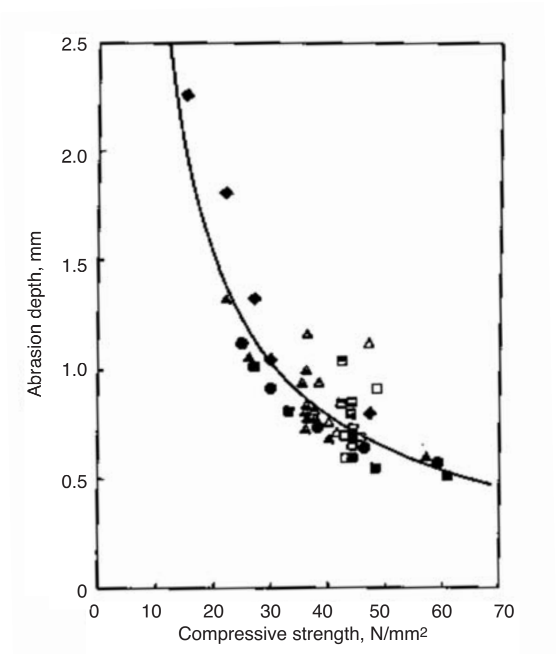

Figure 12—Relationship between the wear resistance and the compressive strength of concrete (Dhir, 1991)

Latex based thin sprayed liner (TSL) can resist much higher stresses than OPC shotcrete of the same thickness. TSL is a product that could possibly be used in the future as a lining with stress supporting capabilities. Unfortunately, TSL would not be able to mitigate the effects of impact and abrasion. (Yilmaz, 2009). If the host rock is exposed to the abovementioned conditions, further support is necessary. Active confinement must be applied to it by means of tendons (rockbolts or anchors). Rock tend to fall out between the tendons in blocky rock and scaling rock environments. Wire mesh and lacing are installed to prevent this. Different tendons are available for different situations, and the responsible rock engineer recommends the correct tendon for the relative application. The tendons come in various lengths to cater for different geological situations. Rigid grouted rock anchors are mostly used to support orepass systems. According to Stacey, conventional rigid rockbolts are usually inappropriate, since impact from rock being passed causes vibrations in the bolt, which destroys the bonding; but that is not the case with fibreglass bolts and wire rope reinforcement. Fibreglass bolts are, however, not used very frequently in the support of orepass systems. Steel grouted tendons and wiremesh covered with a protective lining are used with great success in the mining industry to support orepass systems.

A method used by Murray and Roberts cementation, experts in various fields including the rehabilitation and support of orepass systems, explains how anchors, wire lacing and shotcrete are used to support orepass systems:

- Rock bolting will be done as per the rock engineering recommendations
- Holes of 32 mm in diameter and 1.4 metre long will be drilled at 2.0 metre spacing at areas as directed by the responsible rock engineer
- The drilled holes will be washed clean from drill sludge and grit, 18 mm diameter full column resin high step bars will then be installed
- Support will be done from the top downwards.

Precast concrete pipes, steel 'tubes', and steel rails set in concrete have also been used as liners. Unfortunately, steel items in particular, are considered as foreign material which, when worn and loosened, can also be the cause of hang-ups.

Water

Another threat to the sides of orepass systems is the weathering and decay due to the exposure to the atmosphere and in some cases acidic water entering the orepass system. This is the reason why water should not be allowed to flow into any orepass system, not only due to the weathering effect which is caused by flowing water, but water can also lead to compaction of ore which causes hang-ups, and could even be a safety hazard due to mud rushes. Thus water should be redirected into a sump and then pumped out of the mine.

Excavation method

- *Conventional*—This method is basically blasting the orepass system from the bottom upwards in sections. People got into the orepass system, constructed a stage and drilled, charged and blasted the orepass. This was, however, very dangerous and ventilation of these orepass systems, while people were in them, was very difficult.
- *Drop raising*—This method makes use o a drop raising rig. It is a large drill which is used to drill from one level to the next, and then, similar to the conventional method, sections are blasted at a time. It is, however, safer because no workers need enter the excavation because charging is done from the top.
- *Raise boring*—This method makes use of a pilot hole drilled from the top level by the raise boring machine (seen in Figure 13). Once the pilot hole has reached the next level, as seen in Figure 14, the reamer is connected to the machine and the reamer (seen in

Figure 13—Raise boring machine

Figure 14—Pilot hole

Figure 15) is dragged up to the top level. This is continuous for excavations if the excavation is less than 150 m. This also a very safe method and, because no blasting is required, this method has the advantage of no blast induced fractures on the sides of the orepass system, which could weaken the structure.

Summary of literature study

As seen in Figure 16:

- Orepass systems should be developed perpendicular through weak rock
- Orepass systems should be orientated as close as possible to parallel to the major principal stress
- Legs of ore passes should be dipping between 60°–70°
- Length of the legs should not exceed 45m depending on the angle
- The diameter of the orepass should be at least three times the diameter of the largest rock to pass through the orepass
- Any leg of the orepass system should not be developed closer than three times the combined diameter of the orepass and the diameter of the nearest excavation
- Depending on conditions, appropriate supporting measures should be applied
- Main orepass systems must be developed in de-stressed areas
- Water should be directed away from orepass systems
- Maintenance and refurbishments should be done accordingly
- Orepasses should be raise bored to eliminate blast induced fractures.

Results

A survey was completed on the leg between 110 and 110A levels of the current main orepass closest to the shaft to determine the current state of the orepass. It was expected that the orepass may mine itself through into the main shaft. Figure 17 shows that it is very possible that this is happening. The solid blue column represents the original dimension of the leg of the orepass, and the outer lines represent the current state of the orepass. It is evident that the orepass has almost tripled in size and is mining through to the main shaft.

Figure 18 on the left-hand side next to a man is a rock that fell out of a ventilation hole raise bored between 100 and 105 level. It became obvious that new excavations should carefully be considered before developing starts. This ventilation hole was excavated parallel with the strata, similar to the conditions present at the final leg of the

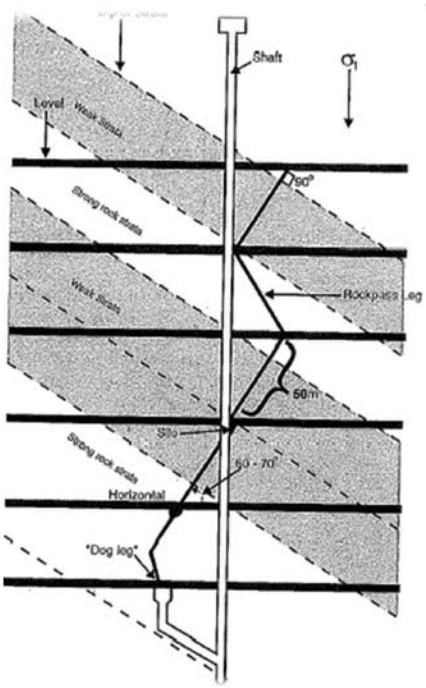

Figure 16—Orientation of an stable orepass system (HAGAN)

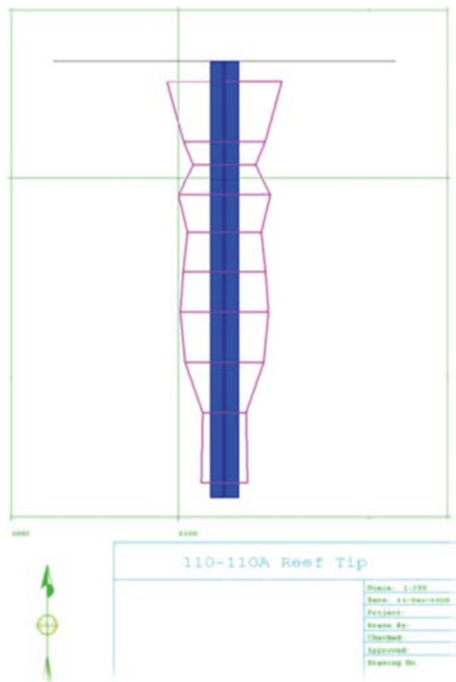

Figure 17—Survey on current state of the leg between 110 and 110A

Figure 15—Reamer

Figure 18—Ventilation hole between 110 and 110A levels

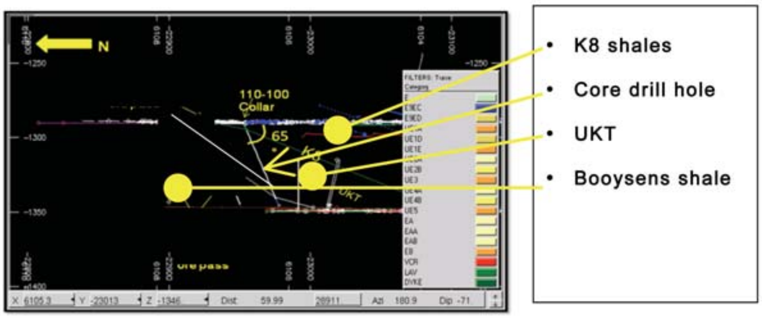

Figure 19—Results from core drilling

Table III

Magnitude, bearing and dip of the principal stresses (Pethö, 2001)

Level	Major	Intermediate	Minor						
	Value [MPa]	Bearing	Dip	Value [MPa]	Bearing	Dip	Value [MPa]	Bearing	Dip
95*	80.8	144	48	58.9	359	30	36.3	265	20
95	21.3	97	53	13.2	204	12	10.2	302	34
100	50.0	136	35	23.3	285	51	15.7	35	16
105	55.2	116	71	44.2	354	11	32	261	16
110									

proposed orepass system. It is proof that a layout perpendicular to the strata is not the best solution and needs to be explored further. It is clear that the conditions present at this particular area are very challenging, and therefore the rest of this paper would focus on the fourth leg of the proposed orepass system.

Geology

Core drilling was done at a dip of 65° from 110-110A level to determine the geological features that may be present. Figure 19 represents the findings of the geologist. He reported that:

- The cover hole has been collared in the K8 shale
- UKT displays horizons of soft sediment deformation throughout the unit
- Soft sediment deformation zones are often associated with faulting
- The localities of the Booysens shale, UKT and the K8 shale represent actual mapped and logged positions.

The geologists' recommendations after his analysis of the core was that: '... to ensure a reasonable life of the orepass between 110 and 110A levels, proper support of the orepass is recommended due to the presence of soft sediment, deformation structures and associated faults.' (Strydom, 2010).

Stresses

In Table III the current magnitude, bearing and dip of the principal stresses can be seen, as well as the virgin stress of level 95 before de-stressing. In the table it is represented by 95*. It is noted that stresses increase the deeper the mine gets. This is due to the fact that the effects of de-stressing at the higher levels where conventional longwall was performed to de-stress the lower levels fade with depth.

From this data, and recommended by the geology and rock engineering department, it is obvious that that support would be needed to ensure a practical life of the fourth leg of the relative main orepass system.

Analysis and evaluation of results

This section deals with the analysis and evaluation of the results discussed earlier. Also comparisons are done on proposed orientations of the final leg of the orepass system, different supporting and lining products available. This is done by rating the different options based on several relative parameters. Firstly, all of the options would be considered, and the best options would be identified and stated. Then the relative parameters must be identified and standards must be defined to which the options can be measured. Each options is then graded on all the identified parameters with a mark ranging from 1–10, 10 being industry best practice, and 1 being unacceptable. The best option would be the option with the highest total sum of the graded parameters. Some parameters may be more important than others. These parameters would then be giving a higher weight. For example, geology may be more important that the other parameters in an specific case; then geology would be allocated a weight of 2. Effectively this means that geology would contribute twice the other parameters to the total sum.

Integrated geological and rock mechanical results

Figure 20 is a 3-D representation of the proposed final leg of the proposed main orepass system. It shows the position of the main geological features in the area and the orientation of the major principle stress. The blue plane represents the transition zone between the UKT and the Booysens shale, and the red plane represents the transition zone between the UKT and the K8 shale. The bearing and the dip of the major principal stress is represented by the three red arrows. As can be seen from Figure 20, the dip of the strata in this area runs almost parallel to the major principal stress.

Figure 21 roughly indicates the two proposed orientations of the fourth leg of the proposed main orepass system relative to the other main excavations, as well as the relative transitions zones of the relative rock strata in the area. It can be seen that it is not situated near any other excavations. It is, however, important to note that if the leg of this orepass system is excavated in the direction of the strata (orientation 1), it would become closer to current excavations and may cause stress build-up in the rock between it and other excavations.

Proposed location, orientation, length and diameter of the final leg of the proposed main orepass system

The proposed diameter of the main orepass systems is 3 m. The length of the orepass will vary from level to level. But for the mentioned leg, the length would be no longer that 40 m. A dog-leg would be excavated with a drill and blast operation, but the rest of the orepass would be raise bored. There are two different orientations considered as shown in Figure 21. Both proposals will dip at 65°. It is clear that the rock is weak, and the stresses are high in this area. In

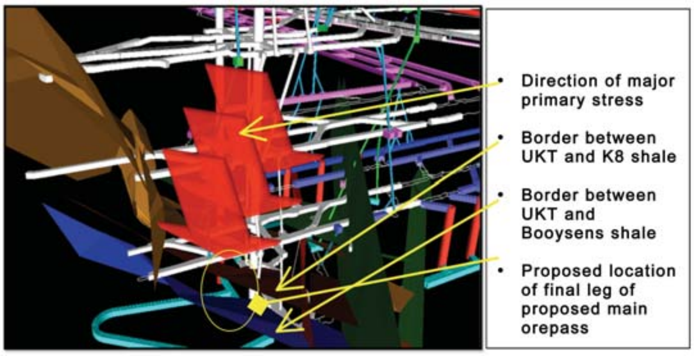

Figure 20—Combined orientation of relative data and major primary stress tensor

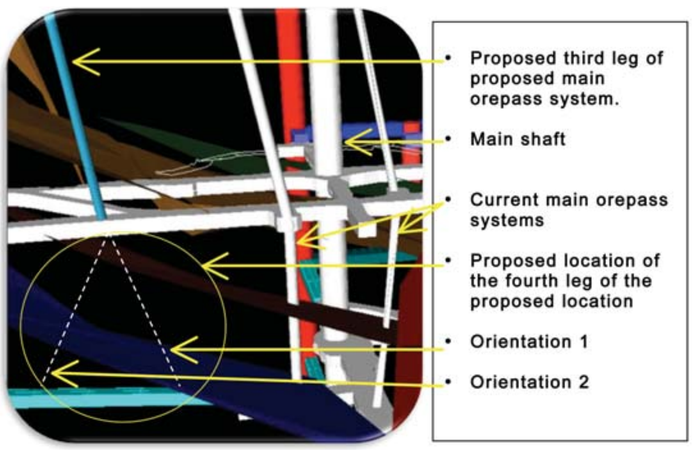

Figure 21—Proposed position of the fourth leg of the proposed orepass system

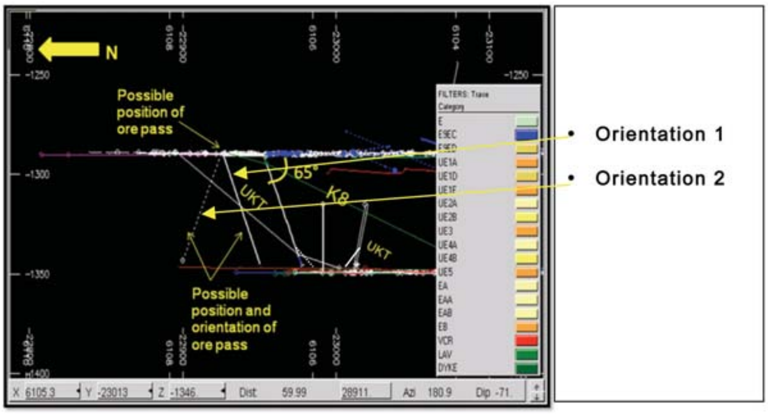

Figure 22—Proposed location and orientation of the final leg

Figure 22 it is clear that the strata and the stresses dip almost parallel to each other. In Table IV the two options, orientation 1 and 2, are compared.

The parameters are:

- ➤ Geological considerations: best practice when in weak geology is to excavate perpendicular through the strata; the weight allocated to this parameter is two, not only because Gay (2006) suggests that geology is the most important parameter of orepass system stability, but also because the ventilation hole seen in Figure 19, which collapsed during excavation, was orientated parallel in a similar geology. The weight for the other parameters would all be one.
  - Orientation 1 is graded 1 out of 10 because it dips very closely (parallel) with the strata.
  - Orientation 2 is graded 8 out of 10 because it dips almost normally with the strata
- ➤ Excavation method: best practice would be raise boring due to the length, required dip and safety advantages (See Table II why drop raising is not an option). Raise boring also comes with the additional advantages of no blast induced fractures in the rocks when an orepass is raise bored.
  - Orientation 1 is graded 10 out of 10 because it is to be raise bored.
  - Orientation 2 is graded 10 out of 10 because it is to be raise bored.
- ➤ Rock engineering considerations: best practice relative to rock engineering is to excavate parallel to σ_1.
  - Orientation 1 is graded 8 out of 10 because it dips almost normal with the major principal stress.
  - Orientation 2 is graded 1 out of 10 because it dips almost parallel to the major principal stress.
- ➤ Dip: best practice is for the orepass leg to dip between 60°–70°.
  - Orientation 1 and 2 is graded 10 out of 10 because it dips between the recommended 60°–70°.
- ➤ Length: best practice is less than 45 m (depending on dip).
  - Orientation 1 is graded 10 out of 10 because it does not exceed the relative length to the proposed dip.
  - Orientation 2 is graded 10 out of 10 because it does not exceed the relative length to the proposed dip.
- ➤ Dog-leg: best practice is to have a Y-leg to protect the boxfront.
  - Orientation 1 is graded 10 out of 10 because a dog-leg is to be excavated.
  - Orientation 2 is graded 10 out of 10 because a dog-leg is to be excavated.
- ➤ Diameter: must be at least 3 times (diameter of the biggest rock to pass through the orepass), best practice is 5 times (diameter of the biggest rock to pass through the orepass).
  - Orientation 1 is graded 5 out of 10 because a suitable diameter is proposed, but not industry best practice.
  - Orientation 2 is graded 5 out of 10 because a suitable diameter is proposed, but not industry best practice.
- ➤ Proximity: best practice: any leg of the orepass system cannot be developed closer than 3 times (combined diameter of the orepass and the diameter of the nearest excavation)
  - Orientation 1 is graded 4 out of 10 despite the starting point of the proposed leg of the orepass starts far away from other excavation, the distance between it and other excavations would decrease as it deepens.
  - Orientation 2 is graded 10 out of 10 because the distance between it and other excavations would increases as it deepens.

Table IV

Comparison of orientation

Parameter	Weight	Orientation 1	Orientation 2
Geological point of view	2	1	8
Excavation method	1	10	10
Rock mechanical point of view	1	8	1
Length	1	10	10
Dog-leg	1	10	10
Dip	1	10	10
Diameter	1	5	5
Proximity	1	4	10
Total		**59**	**72**

Analysis of different options for supporting the relative leg

Six options for supporting the are compared in this section. The options are (The options are explained in appendix A):

- *Option 1*: Do not support the leg.
- *Option 2*: Support the leg with shotcrete lining.
- *Option 3*: Support the leg with anchors, wire lacing and shotcrete lining.
- *Option 4*: Support the leg with anchors, wire lacing, shotcrete lining and a rail liner.
- *Option 5*: Raise bore 6 m diameter hole, fill it with 60 Mpa reinforced concrete, and raise bore the required 3 m diameter hole.
- *Option 6*: raise bore 6 m diameter hole, fill it up with crusher rock and cement it with 60 Mpa concrete, and then raise bore the required 3 m diameter hole.

The parameters are:

- Safety: there is an increased risk for workers should they need to enter an orepass, so best practice is that no worker ever needs to enter the orepass. Allocated weight: 1
  - *Option 1*: although no workers would never need to enter the orepass, an unstable orepass could be a safety hazard, thus it is graded 3 out of 10.
  - *Option 2*: this option would not support the orepass against weak geology or high stresses, and people would enter the orepass, so it is graded 1 out of 10.
  - *Option 3*: this option would render the orepass stable after completion, but people still need to enter it, so it is graded 3 out of 10.
  - *Option 4*: this option would render the orepass stable after completion, but people still need to enter it, and people would also need to enter to unblock it, and the rails increases the risk of hang-ups, so it is graded 2 out of 10.
  - *Option 5*: people would enter the orepass, so it is graded 3 out of 10.
  - *Option 6*: people would never need to enter the orepass, so it is graded a 10 out of 10
- Life of excavation: best practice is that the orepass would last the total LOM without needing maintenance or refurbishments. Allocated weight: 1
  - *Option 1*: the orepass would not last very long, due to no support against impact, abrasion, the weak geology, or the high stresses and is graded a 1 out of 10.
  - *Option 2*: the orepass would not last very long, due to no support against the weak geology, or the high stresses and is graded a 2 out of 10.
  - *Option 3*: maintenance would be required, but the orepass would have a reasonable life, so it is graded 8 out of 10.
  - *Option 4*: maintenance would be required, but the orepass would have a reasonable life, so it is graded 8 out of 10.
  - *Option 5*: it would most likely last the total LOM, so it is graded 9 out of 10
  - *Option 6*: this option was implemented at Kloof with little success, and there is not really a feasible way to maintain an orepass supported like this unless it is filled up, and raise bored again, so it is graded 1 out of 10.
- Proven in industry: best practice, option proven with success in the industry in similar conditions. Allocated weight: 1
  - *Option 1*: is proven that in these conditions the orepass would fail if not supported, so it is graded a 1 out of 10.
  - *Option 2*: is proven that in these conditions the orepass would fail if supported with only a concrete lining, so it is graded a 2 out of 10.
  - *Option 3*: is proven to hold up in similar conditions by contracters and if the main shaft were supported in a similar way, and is exposed to the same conditions except impact and abrasion, and is still is good condition. This option is graded 8 out of 10.
  - *Option 4*: this option is similar to option 3, so it is graded 8 out of 10.
  - *Option 5*: this is a relative new concept, so it is graded a 3 out of 10.
  - *Option 6*: this option is proven not to work, so it is awarded a 1 out of 10.
- Design: Do the conditions justify the option? Allocated weight: 1
  - *Option 1*: the conditions clearly indicate that support is needed; this option is graded 1 out of 10.
  - *Option 2*: the conditions clearly indicate that support is needed; this option is graded 1 out of 10.
  - *Option 3*: the conditions clearly indicate that support is needed; this option is graded 10 out of 10.

Table V

Comparison between supporting options

Parameter	Weight	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Safety	1	3	1	3	2	3	10
Life of excavation	1	1	2	8	8	9	1
Proven in industry	1	1	2	8	8	3	1
Design	1	1	1	10	10	10	10
Foreign objects introduced	1	10	10	5	1	5	10
TOC	1	2	2	7	5	1	1
Maintenance	1	1	1	6	6	10	1
Logistics	1	10	8	6	4	1	1
Total		**30**	**27**	**53**	**44**	**42**	**35**

- *Option 4*: the conditions clearly indicate that support is needed; this option is graded 10 out of 10.
- *Option 5*: the conditions clearly indicate that support is needed; this option is graded 10 out of 10.
- *Option 6*: the conditions clearly indicate that support is needed; this option is graded 10 out of 10.

➤ Foreign objects introduced: Best practice is not to introduce any foreign objects into the orepass system to prevent hang ups. Allocated weight: 1
- *Option 1*: no foreign objects introduced due to support into the orepass system, this option is graded a 10 out of 10.
- *Option 2*: no foreign objects introduced due to support into the orepass system, this option is graded a 10 out of 10.
- *Option 3*: anchors and wire mash are introduced by support, but is also covered with shotcrete, and should be maintained so that the anchors and wiremesh are not exposed, this option is graded 5 out of 10.
- *Option 4*: the rails are exposed to impact and abrasion, these rails could fail and cause hang ups, this option is graded 1 out of 10.
- *Option 5*: this option also introduce foreign objects, but is also covered, so this option is graded 5 out of 10.
- *Option 6*: no foreign objects introduced due to support into the orepass system, this option is graded a 10 out of 10.

➤ Total owning cost (T.O.C): The lower expected total owning cost would be the best option in this category. Allocated weight: 1 (High level cost estimates in appendix B)
- *Option 1*: the capital cost would be the lowest, but the use of the orepass would be lost and expensive alternative solutions must then be made; this option is graded a 3 out of 10.
- *Option 2*: this would be have a low capital cost relative to the other support options, but the lining would be lost due to scaling of the rock, and maintenance would then become very un-economical, this option is graded a 2 out of 10.
- *Option 3*: although the higher capital cost, maintenance would be required only when the affects of impact and abrasion wear away the lining. This option is graded 7 out of 10.
- *Option 4*: this option is similar to option 3, although the capaital cost and expected maintenance is more expensive, so this option is graded 5 out of 10.
- *Option 5*: no expected maintenance required, but extremely expensive capital cost; graded 1 out of 10.
- *Option 6*: expensive as well as expensive maintenance; graded 1 out of 10.

➤ Maintenance and refurbishment required: best practice would be that the orepass would never need to be refurbished. (This is not based on cost; the cost of maintenance has already been covered by the TOC parameter. This parameter handles how production could be inconvenienced by the maintenance of an orepass system. Allocated weight: 1
- *Option 1*: it is expected that the orepass would fail, and a new orepass in a new location must be excavated; this option is graded 1 out of 10.
- *Option 2*: it is expected that the orepass would fail, and a new orepass in a new location must be excavated; this option is graded 1 out of 10.
- *Option 3*: the shotcrete lining must be maintained as needed; this option is graded 6 out of 10.
- *Option 4*: the rail lining must be maintained as needed; this option is graded 6 out of 10.
- *Option 5*: no refurbishment of any kind is expected for this option, so it is graded 10 out of 10.
- *Option 6*: difficult, expensive and time consuming refurbishment is expected, so this option is graded 1 out of 10.

➤ Logistics: all materials must be hoisted down the shaft, the lower the impact on the shaft schedule, the better. Allocated weight: 1
- *Option 1*: this option would have no effect on the shaft schedule, thus it is graded 10 out of 10.
- *Option 2*: relative to the other options, this would require the least amount of material to go down the shaft, so it is graded 8 out of 10.
- *Option 3*: the same amount of material needed, except for tentonds and wire lacing, this option is thus graded 6 out of 10.
- *Option 4*: the same amount of material required for option 3; however, the large number of rails would complicate the shaft schedule severely. This option is graded a 4 out of 10.
- *Option 5*: this option requires a large raise bore machine to go down the shaft, not to mention the large amount of required material. This option is graded 1 out of 10.
- *Option 6*: Same as option 5; 1 out of 10.

Analysis of different lining options

Two products from different suppliers have been selected to be analysed in this section. They are both specially designed, and proven in industry for support against impact and abrasion of orepass systems. Both these cement products would be mixed with andisite aggregate with an average size of 20 mm, and polypropylene fibres.

The options are:

Table VI

Comparison of cement liner products

Parameter	Weight	HSWR	Fonducrete
Cost	1	9	3
Compressive strength	1	7	10
Resistance to wear	1	8	10
Total		**14**	**23**

- High strength wear resistant (HSWR), which is an OPC based concrete.
- Fonducrete, which is a CAC based concrete.

The parameters are:

- Cost: HSWR is three times cheaper that Fonductrete, so HSWR is awarded three times a higher grade.
- Compressive strength: Fonducrete reaches 100 MPa, where HSWR reaches only 70 Mpa after 28 days. Fonducrete is thus awarded a ten, and thus logic dictates that HSWR should be awarded 7.
- Resistance to wear due to impact and abrasion: Fonducrete is awarded 10 according to the studies done by Van Heerden; HSWR is rated a 7 because it is a proven product in the industry.

Conclusions

This section reflects on the report and discusses the conclusions made from the findings.

- It was found from the literature study that several underground conditions play an integral role in the design of a successful main orepass system. It is concluded that as depth increases, complications relative to geotechnical aspects would increase as well.
- It was found that the high stress levels and the weak rock played the biggest role in the damage inflicted on the current main orepass systems.
- It is concluded that, despite the high σ_1 in the particular area, it would be better orientating the final leg of the proposed orepass system in favour of the best practice relating to geology rather than the best practice pertaining to the σ_1, due to the weak rock which was the cause of the collapse of the ventilation hole seen in Figure 19. (See Table V). The main reasoning for this is that there is not sufficient time after excavation to support the orepass, as in the case of the mentioned ventilation hole.
- Earlier it was implied that support would be required in the relevant area, and from Table V it is suggested that the best option for supporting the leg of the proposed orepass would be supporting with anchors, wire mesh and a shotcrete layer.
- It is also concluded from Table V that it would be better not to support the fourth leg of the orepass system at all rather than to just supporting it with a concrete lining.
- According to the comparison of the two linings, Fonducrete is the better lining.

Recommendations

This section provides recommendations on the findings that were analysed during this project.

- It is recommended to follow the industry best practice as far as possible, to ensure that the main orepass systems are placed in favourable conditions and the best orientation so that main orepass system support is not needed, except for lining used to support the main orepass system against impact and abrasion.
- As per the recommendation of the geology and rock engineering department, maximum support is to be applied in the fourth leg of the proposed main orepass system.
- If support for other main orepass systems is judged necessary by South Deep, anchors, wire mesh and shotcrete recommended.
- Although Fonducrete is rated the better concrete, several experts disagree with the results shown in the literature study. Also, the results obtained by the company were done under lab conditions, and there is no guarantee that the same results would be obtained in the difficult conditions of an orepass system. This is why the high cost of Fonducrete is not justified. HSWR is thus recommended due to the fact that it is also proven in industry to protect orepass systems against impact and abrasion and is considerably cheaper.
- It is strongly recommended that the fourth legs of the current main orepass systems between the 110 and 110A levels be refurbished.

Suggestions for further work

It is suggested that the conditions for the other main orepasses that are currently proposed should be obtained and analysed to ensure that the best possible decisions can be made on their design to optimize their performance.

The optimum support materials should be selected, namely:

- If it is decided to make use of a concrete lining, further investigation of the correct lining to be used must be done.

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  - Werner Strydom, Geologist
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  - My mentor: Pieter Oosthuysen, Senior Project Manager

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Appendix A: supporting options compaired earlier

Lining orepass systems with concrete lining (Option 2).

- After excavating the orepass.
- Then the sides are covered with a concrete shotcteted lining.
- Cover the wall of the orepass with poured or shotcreted concrete as ilistrated in Figure 23.

Supporting an orepass with anchors, wire mesh and then lining the orepass (Option 3).

- After excavating the orepass
- Install anchors and wire lacing/mesh
- Cover the wall of the orepass with poured or shotcreted concrete, as illustrated in Figure 24.

Supporting an orepass with anchors, wiremesh and then lining the orepass (Option 4).

- After excavating the orepass
- Install anchors and wire lacing/mesh

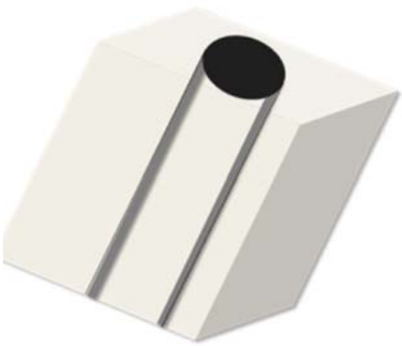

Figure 23—Lining

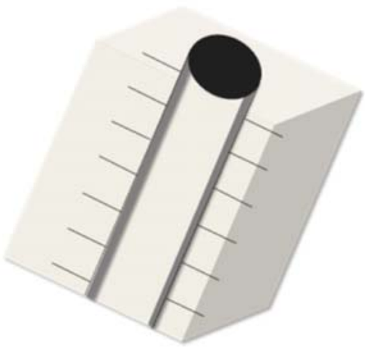

Figure 24—Anchors, wire mesh and concrete lining

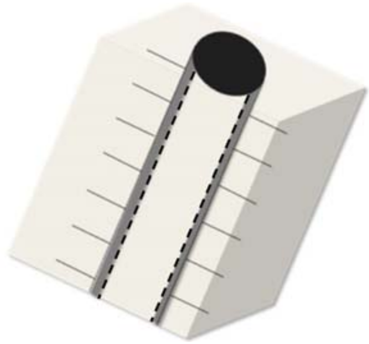

Figure 25—Anchors, wire mesh with a concrete linir with rails in

Figure 26—Reinforced concrete

- Cover the wall of the orepass with poured or shotcreted concrete
- Cover the concrete with steel rails as ilistrated in Figure 25.

Reinforced concrete/ grouted crusher rock (Option 5) See Figure 23.

- Excavate a 6 m diameter hole.
- Fill the hole with reinforced concrete/ grouted crusher rock.
- Excavate the required 3 m diameter hole through the concrete/ grouted crusher rock.

Appendix B: high level cost estimates of support

Rail lining with grouted anchors

- Raise boring of 3Ø hole = R1 000 000
- For a 3 m diameter orepass, 45 m long, using 6 m rails = 570 rails per orepass
  - Circumference of orepass = D*π= 3* π= 9.425m
  - Width of rail = 0.125 m
  - 9.425/.125 = 75.44 = 76 rails/6 m lift
- Delivery cost of rails: R1 539 000
  - Cost of 45 kg/m rail = R450/m = R2 700/rail
- Total cost = R4 589 838.71 rails and anchors

Concrete lining with grouted anchors and wire lacing

- Raise boring of 3Ø hole = R1 000 000
- Anchors and lacing = R500/m
- Liner type X = R25 069.12/m
- 45 m orepass = R2 789 838.71
- Expected life of orepass before maintanace would be required = 15 years

Concrete lining with rails and grouted anchors and lacing

- Raise boring of 3Ø hole = R1 000 000
- For a 3 m diameter orepass, 45 m long, using 6 m rails = 570 rails per orepass
  - Circumference of orepass = D*π= 3* π= 9.425 m
  - 9.425/0.125 = 75.44 = 76 rails/6 m lift (width of - rail = 0.125 m)
- Delivery cost of rails: R1 539 000
  Cost of 45 kg/m rail = R450/m = R2 700/rail
- Lining type X = R 25 069.12/m
- Total cost = R5 717 949.11

Civil (filling up a 6 Ø raisbore hole with grouted crusher rock)

- Raise boring of 6Ø hole = R1 700 000
- Raise boring of 3Ø hole = R1 000 000
- Area = $6^2 * \pi$= 113.1 m²
- Assume length of 45 m
- Volume = 45*113.1 = 5 090 m³
- APF = 0.74 (assuming that all the rocks are spherical and exactly the same size.)
- Volume of concrete needed = (1–0.74)*(5 090) = 1 324 m³

Civil (reinforced concrete option)

- Raise boring of 6Ø hole = R1 700 000
- Raise boring of 3Ø hole = R1 000 000
- Area = $6^2 * \pi$= 113.1 m²
- Assume length of 45 m
- Volume = 45*113.1 = 5 090 m³
- Cost of 90 Mpa reinforced concrete (transported and poured) = R16 200/ m³
- Cost of supporting orepass/m = R610 725
- Cost = R30 182 652

Appendix C: Stratographic column

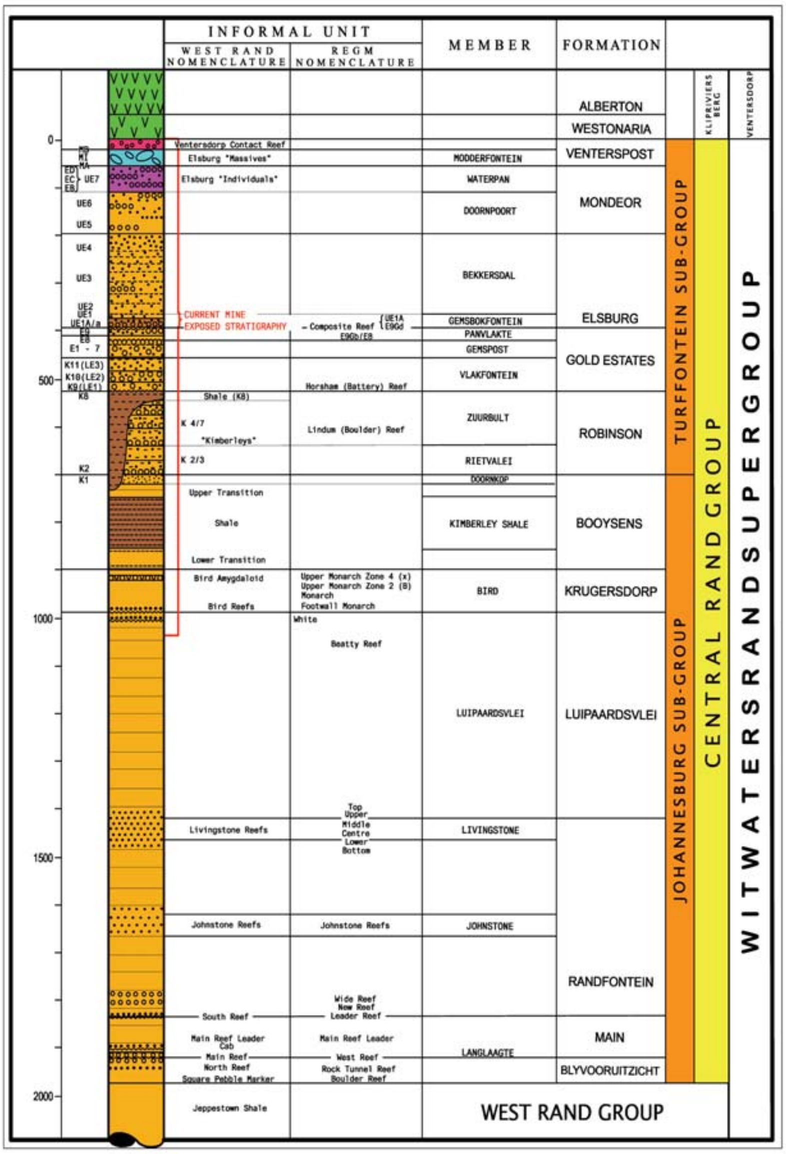

Figure 27—Stratografic column