Introduction

South Deep Gold Mine, managed by the Placer Dome Western Areas Joint Venture, is situated approximately 10 km south of Westonaria, Gauteng Province. South Deep is connected to the neighbouring Randfontein Estates Limited No. 4 Shaft (REL 4) via five haulages, two on 50 Level and three on 58 Level (Figure 1). Several technical investigations had been carried out before and during construction of the plugs in order to reduce the probability of groundwater flow through the boundary pillar between the two mines or through the rock mass immediately around the plugs. This paper describes the geological, hydrogeological and stability investigations carried out to evaluate the structural competence of the boundary pillar.

Dolomitic aquifers overlie both mines and REL 4 in particular has been plagued by large inflows of extraneous water. This shaft started dewatering the overlying Gemsbokfontein West Groundwater Compartment in 1986. Since then the groundwater inflow rate reduced from 150 M l/day to the current 70 M l/day. This rate is expected to reduce further over the next ten years to approximately 48 M l/day, when steady state conditions will be reached.

REL 4 currently pumps in the order of 70-80 M l/day to surface in order to prevent flooding of the mine. The bulk of the water is discharged into the Kleinwesrientspruit. Therefore, the probability of flooding REL 4 should be considered very high should pumping at REL 4 stop. This could be a major threat to mining operations at South Deep.

A pumping rate of 8 M l/day is currently required to remove all mine water from South Deep’s SV1 shaft. The pumping system has a capacity of 20 M l/day for long-term use and, in emergencies, 32 M l/day can be managed for short periods of time. An additional 2 M l/day could be easily managed without any strain on the current system. If an inflow of greater than 2 M l/day occurs, pipe columns and pumping systems would need to be installed on 58 Level, to maintain the main haulage in a serviceable condition. Should the inflow exceed 5 M l/day this will put a significant strain on the SV1 pumping systems and leave very little margin for error. An inflow in excess of 12 M l/day will exceed the current pumping capacity at SV1 and if this continues, partial flooding of South Deep can be expected.

The maximum water pressure on 58 Level, if flooded up to the original dolomitic groundwater table, will be 15 MPa. At the current flow rates, it is anticipated that it may take two months to flood REL 4 if pumping is stopped completely.

The possible closure of REL 4 necessitated the construction of five concrete plugs to prevent the current ingress of groundwater into REL 4 from flooding South Deep mine. Several technical investigations had been carried out before and during construction of the plugs in order to reduce the probability of groundwater flow through the boundary pillar between the two mines or through the rock mass immediately around the plugs. This paper describes the geological, hydrogeological and stability investigations carried out to evaluate the structural competence of the boundary pillar.

Synopsis

The possible closure and subsequent flooding of South Deep Gold Mine’s neighbouring Randfontein Estates Limited No. 4 Shaft (REL 4) necessitated the construction of five concrete plugs in the connecting tunnels to prevent the ingress of groundwater into REL 4 from flooding South Deep mine. Several technical investigations had been carried out before and during construction of the plugs in order to reduce the probability of groundwater flow through the boundary pillar between the two mines or through the rock mass immediately around the plugs. This paper describes the geological, hydrogeological and stability investigations carried out to evaluate the structural competence of the boundary pillar.
Geology, hydrogeology and structural competency of the boundary pillar

If large inflows occur, it will be possible to lower the water level to 58 Level, through drain pipes in the water plugs on 58 Level, allowing time to assess the situation and seal off the inflow where accessible.

Several technical investigations had been carried out before and during the construction of the plugs in order to reduce the probability of groundwater flow through the boundary pillar between the two mines or through the rock mass immediately around the plugs. The technical investigations aimed at evaluating the structural competency of the boundary pillar between the two mines and include the following aspects:

- A review of the mine plans to determine the extent of the pillar as well as mining in its vicinity
- An underground survey of the pillar to assess the ground conditions in and around the pillar
- The identification of geological structures that may act as conduits for water flow and the permeability of these structures as well as the in situ formations
- Numerical analysis of the stress environment in and around the pillar
- A risk assessment to evaluate the risk to South Deep should flooding of the neighbouring mine occur.

Routine investigations included the following:

- Geological mapping of the plug positions
- Drilling and geotechnical assessment of the in situ formations
- Permeability testing of geological features and the formations adjacent to the plugs
- Grouting of the geological structures and pre-routing of permeable zones.

This paper summarizes the technical and routine investigations carried out and describes the methodology for evaluating the competence of the boundary pillar.

Site description and problem statement

Regional geological and geohydrological setting

The lithology and stratigraphy of the surface and near surface geology comprises the Transvaal and Karoo supergroups (Figure 2). These rocks overlie the older Vrentersdorp Lava (Klipriviersberg Group) and the gold bearing conglomerates of the Witwatersrand Supergroup. According to Parsons (1985), the Chuniespoort dolomite attains a thickness of up to a 1 000 m within the study area. Very little dolomitic rock is exposed within the study area, although the entire area is underlain by dolomite. Large portions of the surface are covered by the Rooihoogte Formation, consisting of the Bevets Conglomerate, shale and quartzite. Pebble and boulder beds belonging to the Dwyka Formation, Karoo Supergroup, overlie parts of the Transvaal rocks. There is also a significant accumulation of hillwash and transported sediments within the area.

Figure 2 also shows the major faults that have been mapped. These faults are important in that they hydraulically connect the main dolomite compartment with the southern dolomitic inlier. The faults may also link the dolomitic aquifer with the underlying mine workings and an attempt was made to identify major conduits into the mine. This investigation concentrated mainly on REL No.4 Shaft, since water ingress into this mine is significant. The risk to South Deep is mainly as a result of water ingress into REL 4 and not into South Deep itself.
There are three main water ingress points into REL 4 Shaft, all located in the northern extremity of the mine. The reason for these ingress points being concentrated in the north and northeast of the mine is believed to be related to the thickness of the Venersdorp lava, wedged between the Witwatersrand rocks and the overlying Black Reef and dolomite. The Venersdorp lava thickens towards the south and as a rule of thumb a thickness greater than 50 m will prevent significant inflow of groundwater.

Figure 3 shows a geological section from REL 4 to South Deep that illustrates the geology in depth and in the vicinity of the plugs.

In the vicinity of the boundary pillar a large area has been mined on both sides of the pillar, on different reef horizons. The Venersdorp Contact Reef (VCR) is the uppermost reef horizon. Beneath this there are three reef horizons mined within the ‘Massives’ in the Elsburg formation. These horizons are referred to as the MB, the MI and the MA. Beneath the ‘Massives’, lies the ‘Elsburgs’, also part of the Elsburg formation, in which the EC reef horizon was also mined. Stoping widths on the MB, MI, MA and EC vary considerably and can be up to 6 m.

Conventional stoping was practised on all five reef horizons and a large proportion of the EC horizon was mined.
Geology, hydrogeology and structural competency of the boundary pillar using trackless mechanized mining methods. There is no mining taking place currently within 400 m of the boundary pillar on the South Deep side of the pillar.

North of the boundary pillar, all mining activities stopped approximately two years ago. The boundary position is on the northern side of the demarcated boundary pillar and therefore REL 4 is legally restricted from mining within 9 m of the currently demarcated boundary pillar. Future mining on South Deep may need to be restricted in the vicinity of the boundary pillar to ensure its stability.

The ground is structurally disturbed in the vicinity of the boundary pillar. Several major geological structures traverse the boundary pillar that may act as water conduits between the two mines. Figure 4 shows the available structural geological information in the vicinity of the plugs. In addition to identifying potential conduits, an investigation was also undertaken to evaluate the fault fill material and the erosion probability of the fill material. This aspect is dealt with in more detail later in this report.

**Groundwater modelling**

The water source that is threatening the mining operations is situated in the overlying dolomite formations, in particular the Gemsbokfontein West Groundwater Compartment (see Figure 3).

The Gemsbokfontein West Compartment is bounded by the Panvlakte Dyke in the north, which is located in the immediate vicinity of the Donaldson Dam with a west—north—west to east—south—east strike, which extends to the immediate south of Lenasia. The Gemsbokfontein Dyke and Magazine Dyke form the western and eastern boundaries, respectively. According to Parsons (1986), dolomitic outliers have been mapped to the south of REL 4 Shaft, which forms the southern boundary of the traditional Gemsbokfontein West Compartment. Parsons (1986) concluded that these outliers are hydraulically connected with the main compartment since the dolomites are continuous beneath a syncline of overlying Timeball Hill rocks.

Although a thrust fault separates these two areas, a number of faults such as the Waterpan and Jachtfontein have been recorded by Parsons (1986) as potential groundwater conduits connecting the main dolomitic compartment to the southern outliers. Since the entire dolomitic body is interconnected, the authors are in agreement with the assumption...
made by Parsons (1986) that the southern boundary of the Gemsbokfontein West Compartment is in fact the southern contact with the Rooihoogte rocks. The dolomite has been subjected to extensive karstification prior to the deposition of the overlying Karoo sediments. Although the fresh dolomitic, Karoo and Witwatersrand strata have a water-bearing and storage capacity as a result of secondary structural features such as faults and joints, it is the deeply weathered zones within the dolomites that forms the significant aquifer within the study area. The alkaline dykes, which have subsequently intruded the stratigraphic succession, have resulted in the compartmentalization of the Chuniespoort Dolomites. However, analysis of the observed groundwater levels within the Gemsbokfontein Compartment suggests that there are also further hydraulic subdivisions within the compartment. Whether these variations in aquifer parameters are the result of lithological or structural variations is as yet unknown. The unsaturated zone within the study area range from weathered wad material and Karoo sediments within deep solution cavities or grykes to relatively fresh fractured dolomite between major solution cavities at depth. The shallow weathered aquifer has been formed as a result of the karstification, which has taken place prior to the deposition of the Karoo sediments on top of the Chuniespoort dolomites. There is general agreement that this aquifer is the significant source of water within the Gemsbokfontein Compartment. The weathered aquifer is irregular in nature, but the orientation of the major grykes is parallel to the known structural trends within the dolomite compartment. It has been anticipated that the dolomite approximates a traditional fractured rock aquifer at depth where dissolution has been less pronounced. This transition is likely to occur from some 35 m below surface. The effective base of this aquifer is likely to occur at a depth of some 150 m to 200 m below surface. Although the dolomites are some 900 m to 1100 m thick, it is extremely unlikely that any significant groundwater flow occurs below these depths except along intersecting structural conduits to the underlying mine workings.

Groundwater balance

The water balance used for the purposes of groundwater modelling is based on:

\[
\text{Groundwater outflow} = \text{Groundwater inflow} - \text{Change in storage}
\]

The groundwater outflow from the Gemsbokfontein Compartment is relatively well documented by the historical pumping. The groundwater inflows into the compartment are less well understood but have been quantified over the years through numerous investigations as follows:

- Rainfall recharge into the dolomites within the immediate study area tend to be in the order of 13% to 20% of the mean annual precipitation
- Artificial recharge has been known to occur as a result of the surface water diversions from residential areas towards the Wonderfonteinspruit in the north-western corner of the Gemsbokfontein West Compartment. Estimates for the surface runoff suggest that the runoff percentage is in the order of 10% to 15%

- Some artificial recharge and recirculation have also been documented from the Kleinwesrietspruit and the Leeuspruit. Losses have been measured for the Leeuspruit over time while the losses were estimated for the Kleinwesrietspruit on the basis of preliminary field measurements
- A previous groundwater model undertaken for the Zuurbekom Compartment by the Department of Water Affairs has shown that the leakage across the Magazine Dyke into the Gemsbokfontein West Compartment is in the order of 6 M/day. It is expected that a similar order of magnitude flow across the Panvlakte Dyke would be feasible. No flow across the Gemsbokfontein Dyke is expected.

The average components of the water balance are summarized in Table I.

The above figure of 67 M/day recharge in Table I to the compartment also includes groundwater storage within the dolomitic aquifer. It is estimated that this figure will reduce to approximately 48 M/day once the aquifer has been dewatered.

Numerical modelling

Given the observed groundwater levels within the Gemsbokfontein West Compartment, the dolomitic aquifer has been subdivided into two discrete layers for modelling purposes:

- Layer 1—This layer may be termed the shallow weathered aquifer, which primarily consists of dissolution cavities and wad material. This layer extends from surface to approximately 1535 m amsl
- Layer 2—This layer represents the fractured, unw_weathered dolomite between approximately 1535 m and the mine workings.

The MODFLOW groundwater modelling code was used to carry out numerical analyses. This code could accommodate the interaction between the two aquifers, the influence of rainfall recharge and the leakage from the overlying dolomites into the underlying mine workings.

The Gemsbokfontein, Panvlakte and Magazine dykes were selected as appropriate geohydrological boundaries for the Gemsbokfontein West Compartment. The southern contact between the Chuniespoort Dolomites and the Pretoria strata was taken to be the southern boundary of the groundwater modelling domain.

The observed groundwater levels over time and the historical pumping data from 1986 to 1998 were used to calibrate the model.

<table>
<thead>
<tr>
<th>Groundwater Inflow Source</th>
<th>Volume %</th>
<th>Volume M/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simunye and Westonaria</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Inter compartmental flow</td>
<td>27</td>
<td>15.5</td>
</tr>
<tr>
<td>Leeuspruit</td>
<td>11</td>
<td>7.5</td>
</tr>
<tr>
<td>Kleinwesrietspruit</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Rainfall recharge</td>
<td>51</td>
<td>36</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>67</td>
</tr>
</tbody>
</table>

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Geology, hydrogeology and structural competency of the boundary pillar

Predictive model simulations
Once the groundwater model had been calibrated it can be used for predicting the aquifer’s response to various management options. This model was used to simulate the response that the aquifer will have on the closure and subsequent flooding of REL 4 Shaft. The model was designed primarily for simulating the groundwater table recovery within the natural aquifer/s, but this recovery will commence only once the mined-out area has been flooded.

The void created by mining was therefore also calculated using a digital terrain model (DTM) created from stope peg data. The computer-generated maps were then compared with the mine plans and no obvious deviations were noted. An additional 25% was then added to compensate for footwall development.

The calculated void volume, including footwall development, is presented in Table II.

Groundwater recharge is the major factor governing the inflow of groundwater into the mine. The recharge model, as discussed in the previous section (Table I), formed the basis for the void (mined-out area) flooding rate predictions. The current recharge to the Gemsbokfontein West Compartment is estimated at 67 M l/day. This volume was used in the calibration of the groundwater model and is considered to be representative of the natural conditions. The reported pumping rates are, however, slightly higher due to the storage component in the dolomite aquifer. The reported inflow rates average 75 M l/day. It is expected that this rate will continue during the flooding of the workings although variable rainfall and recharge from surface streams may in the longer term have a small impact on the recharge to the dolomite aquifer. During the flooding of the mine no water will be pumped into the surface streams and the water flow in the Kleinwes Rietspuit and Leeuskop is expected to reduce to non-perennial rainwater flow. Recharge to the dolomite aquifer will therefore be slightly less, but due to the relatively rapid flooding of the workings the effect is unlikely to be noticeable.

It is estimated that the mine void will fill within 17 months, assuming an inflow rate of 75 M l/day and that no pumping will occur during that time. The flooding between 58 and 50 Level will be monitored to ensure that no holings and/or seepage occur through the boundary pillar. This flooding period is approximately 2 months.

The groundwater table recovery within the dolomite aquifer is more difficult to determine without detailed simulations and will vary throughout the compartment. This is due to different geohydrological zones, with different aquifer parameters and the fact that the dolomite aquifer consist of two layers, each with very different characteristics. The deeper dolomite (approximately 1535 m amsl—1400 m amsl) is largely impermeable, with the exception of some fracturing. The weathered dolomite (approximately 1535 m amsl—1560 m amsl) contains large quantities of groundwater and water movement is a lot freer than in the fractured aquifer. Due to the large storage capacity of the weathered dolomite, the rewatering rate will be significantly slower in this zone.

The storativity in the fractured aquifer varies between 0.003 to 0.005, which amounts to groundwater storage of 58 764 567 m³. The storativity in the weathered aquifer varies between 0.015 and 0.02, which amounts to groundwater storage of 27 752 296 m³.

Based on the recovery simulations it appears that the mine will be flooded within 17 months and the dolomite groundwater levels would have fully recovered to their original level of 1 559 m amsl some 58 months later. The significance of the flooding rates is twofold. Firstly it gives an estimate of the time frame during which REL 4 will flood, in particular the portion between 58 and 50 levels. During this time the integrity of the boundary pillar will be tested and contingency plans can be implemented if necessary. The second important issue relates to the water level recovery and the subsequent increase in pressure on the water plugs.

Integrity of the boundary pillar
Several investigations were undertaken prior to and during the course of the plug construction to evaluate the integrity of the boundary pillar and to identify potential conduits. These investigations are summarized below.

Boundary pillar stability analysis
Numerical modelling of the boundary pillar was carried out to determine the extent of fracturing in the boundary pillar and the stress distribution in the pillar. The 3D boundary element elastic numerical modelling program MAP3D was used for this purpose.

Digitized mine plans, covering an area of approximately one square kilometre in the vicinity of the boundary pillar, were used to construct the numerical model. Average stopping widths of between 1.5 m and 6.0 m were used for each of the different horizons. The virgin stress field as determined by stress measurements carried out at South Deep, and typical elastic and material strength properties for quartzite, were used in the analyses.

The following risks were evaluated based on the numerical modelling:

- Water inflow through the rock mass in the boundary pillar—The boundary pillar consists of quartzite material. Intact quartzite material is impermeable. However, flow paths could possibly exist within the rock mass. Possible flow paths include discontinuities in the rock mass and completely failed sections of the boundary pillar.
- Water inflow through discontinuities—It is expected that, if flow through discontinuities does occur, it will

<table>
<thead>
<tr>
<th>Interval</th>
<th>Elevation m amsl</th>
<th>Stoping volume m³</th>
<th>Footwall volume m³</th>
<th>Total m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>58–50 Level</td>
<td>0–201</td>
<td>3 039 879</td>
<td>759 970</td>
<td>3 799 849</td>
</tr>
<tr>
<td>50–48 Level</td>
<td>281–368</td>
<td>3 612 321</td>
<td>908 080</td>
<td>4 520 401</td>
</tr>
<tr>
<td>48–45 Level</td>
<td>368–445</td>
<td>3 390 421</td>
<td>551 487</td>
<td>4 941 908</td>
</tr>
<tr>
<td>45–43 Level</td>
<td>445–518</td>
<td>2 210 947</td>
<td>552 737</td>
<td>2 763 684</td>
</tr>
<tr>
<td>43–41 Level</td>
<td>518–582</td>
<td>2 310 878</td>
<td>577 119</td>
<td>2 888 997</td>
</tr>
<tr>
<td>41–38 Level</td>
<td>582–665</td>
<td>2 394 642</td>
<td>576 161</td>
<td>2 860 803</td>
</tr>
<tr>
<td>38–36 Level</td>
<td>665–738</td>
<td>1 925 433</td>
<td>481 358</td>
<td>2 406 791</td>
</tr>
<tr>
<td>36–32 Level</td>
<td>738–910</td>
<td>5 892 995</td>
<td>1 473 249</td>
<td>7 366 244</td>
</tr>
<tr>
<td>Total volumes</td>
<td></td>
<td>23 523 040</td>
<td>5 880 760</td>
<td>29 403 800</td>
</tr>
</tbody>
</table>

Table II
Calculated void volume for REL 4 Shaft
Geology, hydrogeology and structural competency of the boundary pillar

Figure 5—Schematic presentation of the boundary pillar showing discontinuities and principal stress orientations

be at a low flow rate (\(< 2 \text{ M/day}\)) and will not represent a significant risk to the mine. However, it is possible that higher flow rates through discontinuities containing thick infill/gouge/dyke material could occur. To allow water flow into South Deep, a continuous flow path from a REL 4 excavation to a South Deep excavation must be present. Figure 5 shows the possible discontinuities that could occur in the boundary pillar. The discontinuities include geological features and mining induced fractures. Geological features include faults, dykes joints and bedding planes. (The permeability of the infill/gouge/dyke material of the discontinuities in the pillar is discussed later in this paper.)

If there is no infill/gouge/dyke material or the infill/gouge/dyke material is impermeable, the water pressure must exceed the normal stress acting on the discontinuity to allow water flow. Should REL 4 Shaft become flooded, the maximum water pressure will be 15 MPa. The results of the boundary pillar stability analysis indicate that the minor principal stress (\(\sigma_3\)) within the boundary pillar is well above the maximum water pressure. At the edges of the excavations, \(\sigma_3\) is very low, but increases rapidly within a few metres of the excavation. The water pressure will not exceed the normal stress acting on discontinuities that are more than a few metres from the excavation. Therefore, water will not flow thorough the pillar as a result of this mechanism.

Individual discontinuities may form continuous flow paths; otherwise, networking discontinuities may form continuous flow paths. Individual pillar sub-perpendicular geological features (including sub-horizontal geological features, such as bedding planes) can easily form continuous flow paths between excavations on either side of the boundary pillar. Faults and dykes traversing the boundary pillar will be the predominant pillar sub-perpendicular, sub-vertical geological features.

Geological plans indicate that several faults/dykes traverse the boundary pillar (see Figure 4). Where networking of discontinuities forms a continuous path, the pillar sub-perpendicular geological features will probably form the backbone of the network. These may connect with any of the other discontinuities to form a network. All of the discontinuities in the network would need to be capable of transporting water, to form a continuous flow path.

If a geological structure has very thick infill/gouge/dyke material and this material can be eroded away, a wide channel can be formed, which could support higher flow rates. These geological structures must be permeable initially and water must be flowing through them. The water will then gradually erode the material away, forming a wide channel, increasing the permeability of the geological structure significantly. Only a few of the geological features that are permeable are likely to have thick infill/gouge/dyke material that can easily be eroded. Alternatively, higher flow rates could possibly occur if the permeability of a geological structure increases as a result of major seismic action. For this to occur a large seismic event (\(> M 3.5\)), would need to occur on a geological structure within the boundary pillar. The mining area has a history of low seismicity and large seismic events are unlikely to occur in this area. This risk is considered unlikely as seismic activity in this area has always been low and there is no mining planned in the vicinity of the boundary pillar. Low probabilities were therefore assigned to the occurrence of this event.

Water inflow through failed sections of the boundary pillar—If a section of the boundary pillar suddenly failed under high water pressure, a sudden inflow of water would occur at extremely high flow rates (\(> 12 \text{ M/day}\)). The consequences of this would be severe, resulting in rapid flooding and possible loss of life. However, due to the thickness of the pillar, it is practically impossible for this flow mechanism to occur at South Deep. Complete disintegration of the boundary pillar can occur only if extensive failure throughout the pillar has occurred and the pillar fragments are eroded away by water action. Ultimately, the pillar would become extremely narrow and weak enough for the water pressure to force an opening in the pillar. The section of boundary pillar would need to have been cut very narrowly initially for this process to be possible. The narrowest section of the pillar is 36 m.
Geology, hydrogeology and structural competency of the boundary pillar

- Water inflow through connecting excavations in the pillar—There are no connections between stoping excavations from either side of the boundary pillar indicated on the survey plans. It is considered unlikely that there are unknown connections between excavations. In the unlikely event that there are unknown connections, water will gradually start flowing through the connections as the water level rises during flooding up to 50 Level. It will be possible to drain the water to below the connections. These connections would need to be sealed off or the inflow would need to be managed by continued pumping at REL 4 Shaft. Once the inflow has been sealed off, controlled flooding of REL 4 Shaft could be continued. Monitoring of the inflow of water in the cross-cuts and drives will be necessary.

The following conclusions were drawn from the numerical modelling:

- In the narrowest sections of the boundary pillar, the minor principal stress at the skin of the excavations is low, but increases rapidly for a few metres and then decreases gradually towards the centre of the pillar
- With the exception of the skins of the excavations, the minor principal stress is greater than 25 MPa throughout the pillar
- Low strength factors, which represent the zone of failure (fracturing) is limited to the skin of the excavations
- The fracturing appears to have stabilized and further propagation of fracturing is not anticipated
- In the centre of the boundary pillar, high strength factors are shown, which indicates that the inner core of the boundary pillar is solid
- It is expected that a pillar of this size would be stable.

Geology/geohydrology methodology

The detailed geological and geohydrological investigations conducted at the five plug sites included three main components:

- Geological mapping of the plug sites
- Drilling and geotechnical logging of the borehole core
- Permeability testing and pregrouting of the plug sites.

The following is a brief description of the methodology followed during the above investigations.

Geological mapping

Geological mapping of the boundary pillar was initially required to define an area within the pillar that is geologically the least disturbed. The initial mapping to determine the pillar position was followed up with detailed mapping of the actual plug site. Geological features that were identified included the following:

- Fault classification—faults were classified in terms of the following characteristics.
  - Orientation
  - Dip direction and degrees
  - Displacement, both vertical and lateral
  - Type of fault, normal, reverse or bedding plane fault
  - Fault fill, such as quartz, fault gouge, breccia, mylonite, etc.
- Dyke classification—Dykes were classified in terms of the following characteristics.
  - Orientation.
  - Dip direction and degrees.
  - Displacement, both vertical and lateral.
  - Thickness of the dyke.
  - Dyke contacts were described.
  - General condition of the dyke was described, i.e. blocky, homogeneous, fractured, etc.

The geological mapping of the 58 West 1, 58 West 2, 58 East and 50 Level plug sites are presented in Figures 6, 7, 8 and 9, respectively.

Figure 6—Geological mapping of the 58 West 1 plug site
Geology, hydrogeology and structural competency of the boundary pillar

A brief summary of the local geological discontinuities is given below for each plug site.

➤ 58 West 1 plug (Figure 6). The border dyke within the boundary pillar is near its mid-section. Some seepage was associated with the dyke and, therefore, the plug was located on the dry side of the dyke. One fracture of concern exists near the loopway breakaway and was required to be permeability tested.

➤ 58 West 2 plug (Figure 7). Some well-defined fractures are present but all appeared to be fairly tight with no significant movement along the fractures. The dyke within the boundary pillar falls on the dry side of the proposed plug. No seepage was noted in the areas of the boundary dyke.

➤ 58 East plug (Figure 8). This site exhibited few signs of disturbance. One structure with mylonite and quartz veining was visible in the hangingwall. There was some seepage noted from some of the fractures, which may link to the South Deep workings. Permeability testing was therefore required. No seepage was noted around the boundary dyke. A nearby stub tunnel was not judged to be a problem because no intermediate structural discontinuities were discovered.

➤ 50 Level East and West plugs (Figure 9). Both plugs on 50 Level are situated within the Klipriviersberg Lavas. Due to the fact that no mining has taken place in close proximity to the proposed sites, these plugs do not necessarily have to be within the boundary pillar. Both plugs were therefore placed on the South Deep side of the pillar, just to the north of the existing water doors. F1, F2 and F3 are prominent NE–SW striking faults within the plug area. Both F1 and F2 are vertical faults. F3 dips to the SE at a flat angle of 30°. None of the faults has any coating and all are tight on both sidewalls. F4, F5 and F6 are prominent faults on the wet side of the proposed plug. F5 is NE–SW striking and F4 and F6 are NW–SE striking faults. The faults are vertical or near vertical without any coating and appear to be tight.

Geotechnical core logging, permeability testing and pre-grouting

The permeability of the geological features within the plug areas was tested through the drilling of boreholes into faults and fractures based on the geological mapping. The rationale for this approach was based on the observation that the in situ rock is largely impermeable and that small-scale fracturing will be sealed by grouting in the later construction phases.

Each borehole was then geotechnically logged. Based on the geotechnical logging a ‘rock mass classification’ was carried out. The rock mass classification is based on the average fracture spacing (AFS) and the rock quality designation (ROD) as per Tables III and IV, respectively. The boreholes were then divided into zones with similar rock quality properties for permeability testing.

Permeability testing was conducted over the entire length or portions of the boreholes. The geotechnical logging highlighted potential permeable zones and the permeability testing attempted to quantify the risk of groundwater flow through those zones.

The Lugeon pressure test was originally designed for determining the permeability of a rock mass and for assessing the need for foundation grouting at dam sites. It comprises the calculation of Lugeon values for each of five test runs at increasing and then decreasing pressures, followed by interpretation of the pattern of results, and hence selection of an appropriate representative permeability. The Lugeon water test procedure has been described by Houlsby (1976). The Lugeon Value could be calculated as follows:

\[
\text{Lugeon value} = \frac{\text{Water taken} \times 10 \text{ (litres/metre/min)}}{\text{Test pressure (bars)}}
\]

The plugs on 58 Level will ultimately be subjected to pressures of 15 MPa and the following test pressures were therefore recommended:

➤ Pressure a = 5 MPa
➤ Pressure b = 10 MPa
➤ Pressure c = 15 MPa.
Geology, hydrogeology and structural competency of the boundary pillar

Figure 8—Geological mapping of the 58 east plug site

Figure 9—Geological mapping of the 50 Level plug sites

Table III
Classification of fracture spacing

<table>
<thead>
<tr>
<th>Description</th>
<th>Spacing</th>
<th>AFS</th>
<th>Rock mass grading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very wide</td>
<td>&gt;3m</td>
<td>&gt;333</td>
<td>Solid</td>
</tr>
<tr>
<td>Wide</td>
<td>1–3m</td>
<td>100–333</td>
<td>Massive</td>
</tr>
<tr>
<td>Moderately close</td>
<td>0.3–1m</td>
<td>33–100</td>
<td>Blocky/seamy</td>
</tr>
<tr>
<td>Close</td>
<td>5–30cm</td>
<td>5–33</td>
<td>Fractured</td>
</tr>
<tr>
<td>Very close</td>
<td>&lt;5cm</td>
<td>&lt;5</td>
<td>Crushed and shattered</td>
</tr>
</tbody>
</table>

Table IV
Rock quality designation classification

<table>
<thead>
<tr>
<th>RQD</th>
<th>Rock Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;25%</td>
<td>Very poor</td>
</tr>
<tr>
<td>25%–50%</td>
<td>Poor</td>
</tr>
<tr>
<td>50%–75%</td>
<td>Fair</td>
</tr>
<tr>
<td>75%–90%</td>
<td>Good</td>
</tr>
<tr>
<td>90%–100%</td>
<td>Very good</td>
</tr>
</tbody>
</table>
Geology, hydrogeology and structural competency of the boundary pillar

These pressures were used only as a guideline and in certain very permeable borehole intervals, these high pressures were not achievable. The permeability could, however, also be calculated at lower pressures. It was decided that all permeable zones with Lugeon values higher than 1 had to be grouted.

While the fracture zone immediately around the tunnel (≤ 2 m) was to be sealed routinely during the grouting phase of plug construction, Lugeon measurements were taken to determine the potential risk of groundwater seepage via more remote geological features, and whether pregrouting of these discontinuities was required to reduce the residual permeability of the surrounding rock mass.

A brief summary of the permeability and pregrouting results is given below.

- **58 West 1 plug**—The rock was tight although the boundary dyke crossed the plug area. Testing showed the dyke to be competent and relatively impermeable (0–1 Lugeon). As seepage may occur along the dyke boundaries, pregrouting of the dyke contacts was carried out beyond the 3rd segment via 50 holes (9 m long) using 1 559 kg of cement (pregrout water/cement ratios = 1.0 to 0.4 by weight).

- **58 West 2 plug**—The southern wall at the second segment was fairly permeable (up to 6 Lugeons). Therefore, pregrouting up to 9 m from the perimeter of the plug was carried out via a ring of 12 holes for the 2nd segment using a total of 135 kg of cement. For the 3rd segment of the plug, two permeable faults and other permeable zones were pregrouted via 35 holes (9 m long) using 1721 kg of cement.

- **58 East plug**—The results indicated relatively impermeable conditions but seepage, noted at the fourth segment (2 Lugeons), required pregrouting to treat locally the approximate east-west trending faults. 300 kg of cement were injected via a ring of eight holes (9 m long).

- **50 Level plugs**—The permeability testing has shown that the rocks are competent and impermeable within both plug sites. All the boreholes were grouted, but not redrilled or retested. 540 kg of cement were injected via a ring of eight holes (9 m long).

The overall effectiveness of the pregrouting at South Deep was required to be verified by single-pressure water tests to confirm that the residual permeability of the grouted zone was acceptable. If not, the borehole stage was re-grouted until the specified residual permeability of 1 Lugeon was attained using refusal pressures up to 25 MPa.

**Mineralogical study**

The aim of the mineralogical study was to determine the common types of fault fills and the erodability of these fills over time and when exposed to acidic mine water. The mineral composition was determined by XRD and by microscopy. The five samples collected from underground fall into three categories:

- Quartz vein type, mainly quartz and a minor amount of pyrite
- Quartz veined schist, mainly quartz, chlorite
- Schist type, mainly quartz, chloritoid and phyllosilicate minerals, e.g., muscovite, chlorite, kaolinite.

The major factors that govern the mineral corrosive characteristics are:

- Mineral reaction rates
- Water quality
- Mineral surface areas and
- Exposure to the reaction water.

The corrosivity of minerals in the samples is studied and described in the base case and mine water scenarios. According to Lasaga (1984), minerals in terms of their dissolution rates can be arranged in order as follows:

Nepheline > anorthite > diopside > enstatite > albite > K-feldspar > forsterite > muscovite > quartz.

Albite, K-feldspar, muscovite and quartz have much lower dissolution rates, i.e. they are not easily corroded by water.

The mineral dissolution rates can also be quantitatively described in mean lifetime of a 1 mm crystal in diameter at pH 5, 25°C in Table V (Lasaga, 1984). The mean life of a 1-mm crystal for quartz, muscovite, K-feldspar, albite are in the range of 80 000 years to 34 million years. According to the mineral reaction rate constants (rate-con) in Table V, we can safely assume that all the minerals occurring in the samples have the long life for dissolution and corrosion by water because quartz, kaolinite and illite all have slower reaction rates. No data for kinetic reaction rates of chloritoid and pyrophyllite are available, but we can safely assume that chloritoid and pyrophyllite are also slow in dissolution.

### Table V

**Lifetime of a 1-mm crystal of minerals at pH 5 and 25°C (Lasaga, 1984)**

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Chemical formula</th>
<th>Reaction rate-con</th>
<th>Lifetime (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>SiO₂</td>
<td>4.1x10⁻¹⁴</td>
<td>34 million</td>
</tr>
<tr>
<td>Muscovite</td>
<td>KAl₃(Si₃O₁₀)(OH)₂</td>
<td>2.56x10⁻¹³</td>
<td>2.7 million</td>
</tr>
<tr>
<td>K-feldspar</td>
<td>NaAlSi₃O₈</td>
<td>1.67x10⁻¹²</td>
<td>520000</td>
</tr>
<tr>
<td>Albite</td>
<td>NaAlSi₃O₈</td>
<td>1.19x10⁻¹¹</td>
<td>80000</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>Al₂(Si₂O₅)(OH)₄</td>
<td>1x10⁻¹³</td>
<td>Similar to muscovite</td>
</tr>
<tr>
<td>Chlorite (Clinoclin-14A)</td>
<td>Mg₃Al₅Si₄O₁₆(OH)₈</td>
<td>4.1x10⁻¹⁷</td>
<td>&gt;Quartz</td>
</tr>
<tr>
<td>Chloritoid</td>
<td>(Fe,Mg,Mn)₃Al₅Si₆O₁₆(OH)₈</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Pyrite</td>
<td>Fe₂₅₂</td>
<td>6x10⁻¹⁶</td>
<td>&gt;Quartz</td>
</tr>
<tr>
<td>Pyrophyllite</td>
<td>Al₄(Si₂O₇)(OH)₄</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>Al₄(Si₂O₇)(OH)₄</td>
<td>1x10⁻¹³</td>
<td>Similar to muscovite</td>
</tr>
</tbody>
</table>
Geology, hydrogeology and structural competency of the boundary pillar

No calcite or other carbonate minerals, which have much higher dissolution rates, were identified in the 5 samples. The calcite reaction rates \( k \) for dissolution (Appelo and Postman, 1993) are:

\[
\begin{align*}
\text{K}_1 & = 0.0510 \quad (\text{pH}<3.5) \\
\text{K}_2 & = 3.32053 \times 10^{-7} \quad (\text{pH}>3.5) \\
\text{K}_3 & = 1.1919 \times 10^{-7} \quad (\text{simple drolysis of calcite}).
\end{align*}
\]

In the current mine water quality at pH 3 (Table VI), the kinetic reaction rate will be large at about 0.0510 \( K_1 \), i.e. very high dissolution rate while the reaction rate at pH >3.5 at the reduced condition will be at about 2.12863e-7, i.e. low dissolution rate (by combination of \( K_2 \) and \( K_3 \)) when the plug will be fully flooded. The reduced condition will occur in the overall situation when the plug is flooded and also is fully functional.

Regarding the actual scenario, the following data with certain assumptions have been used in the geochemical model in this study:

- Actual mine water was collected and this data was used as initial water quality (Table VI).
- The average mineral compositions determined by XRD are used in this study.
- 20% of porosity of rock.
- Specific mineral surface areas are: 1 500 cm\(^2\)/g (quartz, K-feldspar), 20 000 cm\(^2\)/g (kaolinite, muscovite, pyrophyllite), 10 000 cm\(^2\)/g (clinochlore-14A).

Geochemical modelling has been carried out on the mine water scenario, i.e. using current water quality. The results are presented in Figure 10.

Figure 10a is a diagram of the cumulative mass of an individual mineral reacted over a period of 100 years, and indicates that quartz has the lowest reaction rate while chlorite has the highest. The rest of the minerals have intermediate reaction rates.

Figure 10b is a diagram of the mineral reaction rates over a period of 100 years. It indicates that kaolinite and K-feldspar reaction rates increase over the first 5 years and then start to drop. However, the chlorite (clinochlore-14A) reaction rate increases over years while the other minerals’ reaction rates decrease.

Figure 10c is a diagram of the total reacted mass over 100 years. 1000 grams of the mineral materials will be dissolved in a litre of pore water over the 100 year period. If a scale is given, only about 2 cm of the rock materials in thickness exposed to water will be potentially dissolved over 100 years.

Conclusions

Based on the above results, a number of conclusions can be reached for the mineralogy of the samples and mineral corrosive characteristics:

- Three types of the materials are identified: quartz vein type (sample 1E-23), quartz-veined schist (samples 8E-313, 5E-140) and schist type (samples 10E-440, 9E-370). The major minerals identified in the samples are quartz, phyllosilicate minerals (chlorite, muscovite, kaolinite), silicate minerals (K-feldspar, clinochlore), sulphide mineral (pyrite). No carbonate minerals, which are usually easily dissolved in water, specifically in acid conditions, were identified in this study.

- The mineral dissolution rates (corrosivity) are relatively low at both the base case scenario and mine water condition. This means that the minerals in the samples will not be readily dissolved over a period of 100 years.
Geology, hydrogeology and structural competency of the boundary pillar

Boundary pillar stability analysis—This investigation utilized numerical modelling of the boundary pillar to determine the extent of fracturing in the pillar and the stress distribution in the pillar. It concluded that in the narrowest sections of the boundary pillar, the minor principal stress at the skin of the excavations is low, but increases rapidly for a few metres and then decreases gradually towards the centre of the pillar. With the exception of the skins of the excavations, the minor principal stress is greater than 25 MPa throughout the pillar. Low strength factors, which represent the zone of failure (fracturing) is limited to the skin of the excavations. The fracturing appears to have stabilized and further propagation of fracturing is not anticipated. In the centre of the boundary pillar, high strength factors are shown, which indicates that the inner core of the boundary pillar is solid. It concluded that a pillar of this size would be stable.

Drilling and permeability testing—Geological features within the actual plug were drilled and geotechnically logged. Zones with poor rock quality were identified and subjected to pressure testing. Portions of the immediate hangingwall, sidewall or footwall that proved to be permeable (Lugeon > 1) were grouted. Additional boreholes were drilled into these zones and grouted and retested at 3 m intervals. This work was undertaken prior to the actual plug construction and supplemented the plug tightening that followed.

Mineralogical study—There is a possibility that water might flow through the pillar via geological structures such as faults. It was therefore decided to investigate the fracturing through the boundary pillar, specifically the fault fill material. The latter study aimed at assessing the possibility of the fill material eroding over time and when exposed to acidic mine water. Type samples were collected and analysed through microscopy and XRD to identify the minerals constituting the fill material. Geochemical modelling concluded that the mineral dissolution rates (corrosivity) are relatively low at both the base case scenario and mine water condition. This means that the minerals in the samples will not be readily dissolved over a period of 100 years.

With reference to the above-mentioned investigations, it is the opinion of the authors of this paper that potential water seepage through the boundary pillar is considered negligible.

Summary

The integrity of the boundary pillar in terms of the potential for water seepage after flooding was evaluated by a series of investigations. The following points summarize the main conclusions from each investigation.

- Groundwater modelling—A groundwater model was set up to determine the rate of flooding of REL 4 and the overlying dolomite aquifer as well as to assess the risk that the flooding of REL 4 will have on the neighbouring South Deep. The study also assessed the potential for increased groundwater ingress into the South Deep workings via geological structures once flooding has occurred. The study concluded that the geological setting does not support a drastic increase of groundwater after flooding. The mine void will take approximately 2 months to flood to 50 Level and a further 15 months before REL 4 is completely flooded. The dolomite water level will be fully recovered within 6 years after flooding commences.

Figure 10—Diagrams showing masses of the reacted minerals in fluid (Figure 10a), mineral reaction rates (Figure 10b) and total mass of the reacted minerals per litre of pore water (Figure 10c) against years

References


The Pittsburgh International Coal Conference will be held in Sandton next year in parallel with the biennial SA Coal Processing Conference and Exhibition.

The Pittsburgh conference, expected to draw delegates from around the world, will showcase the coal industry and cover the entire spectrum of coal, from geological exploration through to the end user and export.

It will be co-hosted by the South African Coal Processing Society (SACPS) and will be split into two concurrent sessions, with the Society taking responsibility for arranging the coal processing section of the conference.

Dave Tudor, immediate past chairperson of the SACPS, says the conference will act as a platform for academics and producers to present their latest research. ‘Researchers of world renown are expected to present papers covering the full spectrum of the industry.

‘The SA coal export market is a significant contributor to global production and is growing, largely thanks to the planned expansion at the Richards Bay coal terminal,’ he says.

The SACPS held its first biennial coal processing conference and expo in Secunda last year and attracted 200 delegates from the local coal industry. ‘The international conference will be held from 10 to 14 September next year. It will draw at least double this number of delegates from all corners of the globe, where coal is either mined, processed, imported or exported. It is envisaged that all major coal producing countries will be represented at the conference.’

Delegates will have the opportunity to join the planned technical tours to Sasol Secunda, Witbank and Ellisras to gain first-hand insight into the local coal industry. A number of large players and equipment suppliers have expressed their support to keep costs for delegates as reasonable as possible.

Chris Reinecke, who heads the SA organizing committee for the Pittsburgh conference, says the coal industry is currently enjoying sustained high prices for its products.

‘There is growing demand for the product, especially since China—which was a supplier—had its role reversed and has become a substantial importer to feed its rampant manufacturing sector.

‘Coal is the powerhouse that drives the resources industry. The gold, diamond, base metal and ferro-metal sectors all require the coal industry to perform in order to supply sufficient power for them to function effectively.’

The conference will be staged at the Sandton Convention Centre (SCC) and the exhibition will be housed in the Pavilion Centre at the SCC. The expo, headed by John Kaplan of Specialised Exhibitions, plans to showcase coalmining equipment from mining operations, coal processing and shipping equipment.

Kaplan says the expo will create a forum for customers to interact with suppliers and to gain insight into current trends and technology. ‘As a significant player in the global coal industry, it is important for South Africa to exchange knowledge and interact with all role players.’

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