REPROCESSING KIMBERLITE TAILINGS: A SQUARE CONTAMINANT SOURCE IN A BIG HOLE?

T. HARCK[1], M. PETERS[2], G. HUBERT[1], L. BURGER[1], L. OCHIENG'[1] and T. GERMISHUYSE[1]

[1]Golder Associates Africa (Pty) Ltd
Johannesburg, Gauteng, South Africa; E-mail: tharck@golder.co.za
[2]De Beers Kimberley Mines
Kimberley, Northern Cape, South Africa; E-mail: michelle.peters@debeersgroup.com

ABSTRACT

The mining town of Kimberley has had a tumultuous and colourful history. The first recorded diamond find was in 1866. Since then the hillock known as Colesberg Kopje has become the famous Big Hole. Five other kimberlite pipes have subsequently been mined out. Remnant piles of mine waste, known as tailings, are scattered throughout the town. In recent times, a finer-grained waste (slimes) has been deposited to the southeast.

The groundwater impact of these wastes is the focus of considerable attention by Kimberley Mines. In the past, common belief held that the tailings and slimes were inert and that seepage from these wastes was not of concern. It has been suspected that tailings and slimes may have significant sulphide contents and exposure to rain and oxygen for more than a century may have led to the generation of acid seepage. However, neutralisation potential in the wastes and the arid environment has prevented direct observation of AMD.

Diamond recovery at Kimberley has shifted from kimberlite mining to reprocessing of the old tailings. It has been proposed that the reprocessed tailings be returned to the open pits of the mined out kimberlite pipes. The implications of this proposal on groundwater quality over the long-term are not clear. Indeed, the deeper hydrogeology of the Kimberley area had not been investigated until recently.

A conceptual model of the disposal of the reprocessed tailings is presented. This combines recent hydrogeological investigations in the Kimberley area and the results of geochemical characterisation of the tailings and slimes.

1. INTRODUCTION

The town of Kimberley, in South Africa's Northern Cape Province, has had a long mining history. The first recorded diamond find was in 1866 associated with "blue ground" or kimberlite. For the first time in history, diamonds were mined by opencast methods, following the kimberlite pipe. The outcrop of the pipe at surface, a hillock known as Colesberg Kopje, soon disappeared and was turned into a pit. The result was the Big Hole, a vast crater dug entirely with picks and shovels. Approximately 3 000 kg of diamonds were extracted from this opencast until it closed in 1914. It is the largest hand-dug excavation in the world.

The legacy of this past lies in the remnant piles of mine waste, known as tailings, scattered throughout the town. In recent times, a finer-grained waste (slimes) has been deposited to the southeast. Diamond recovery at Kimberley has shifted from kimberlite mining to reprocessing of the old tailings. It has been proposed that the reprocessed tailings be returned to the open pits of the mined out kimberlite pipes.

Kimberley Mines, a division of De Beers Consolidated Mines, is a diamond mining operation, registered as a mine in 1888, located in Kimberley. The mine is situated the Lower Vaal water management area in the C52L quaternary drainage catchment. No natural drainage lines traverse the mine area. The Kimberley area is characterized by relatively low rainfall and extreme temperature ranges between summer and winter.

Kimberley Mines comprises two dormant mines namely: Kimberley Mine; and De Beers Mine. Opencast as well as underground mining activities have ceased and tailings resource recovery operations are taking place at Kimberley Mines. The tailings material is transported to the Recovery Plant, by means of loading and hauling, where it is stockpiled for treatment. The fine residue (slime) after treatment is disposed of as a paste. The coarse residue (tailings) is disposed to a stockpile.

There are five mine pits in Kimberley. None of the pits are operational. Characteristics of the pits are summarised in Table 1.

Table 1. Characteristics of the Kimberley mining pits.

Pits	Depth m	Dewatering rate m^3/month	Comment
Kimberley Pit	200	9 000	The “Big Hole”, oldest, historical monument
DeBeers Pit	800	7 500	Tailings disposal since 2000
Bultfontein Pit	-	39 000	Used for disposal of solid waste
DuToits Pan Pit	-		
Wesselton Pit	150		

The geology in the vicinity of the pits is summarised in Figure 1.

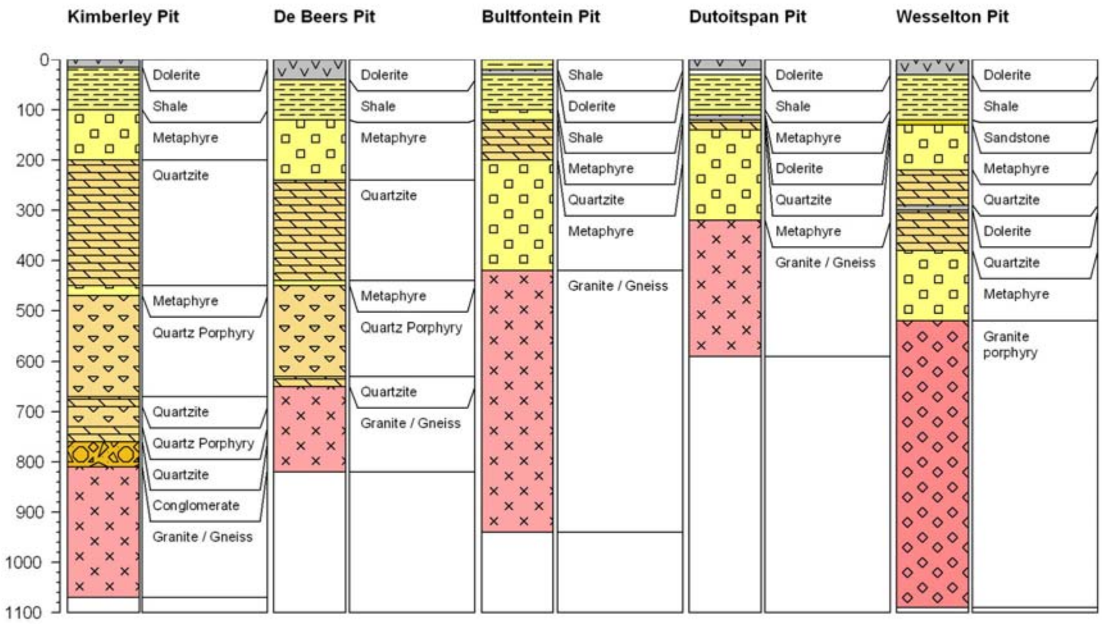

Figure 1. Summary geology at the Kimberley pits.

As mines approach closure, rehabilitation/rectification of mining legacy is being addressed. This is a process that will take several years. Significant resources of unrecovered diamonds are present in the remnant tailings facilities and can now be recovered using present-day technology. Appropriate management of the reprocessed tailings is now required. One proposal is to return the reprocessed tailings to the open cast pits.

This paper describes a study conducted to assess the potential impact on groundwater quality of this proposed management option.

2. METHODS

The study focused on two aspects: characterising the local hydrogeology and characterising the drainage quality from the tailings.

Hydrogeology

The hydrogeology of the Kimberley area was assessed through a programme of targeted borehole drilling, testing and groundwater sampling. Prior to the field programme, a review of available groundwater information was conducted. The outcome of the hydrogeology aspect of the study was to develop a conceptual hydrogeological model of the area containing the open pits.

Tailings Drainage Quality

Tailings reprocessing is conducted using gravity separation methods with water as the transport medium. As such, no significant chemical changes were anticipated from reprocessing and samples of existing tailings resources prior to reprocessing were assumed to be a suitable surrogate of tailings material that may be deposited in open pits.

Samples of tailings were collected from open pits excavated into tailings resources. Field observations of the movement of drainage within the tailings were recorded. The samples were submitted for a range of laboratory testing, including:

- Mineralogy by X-ray diffraction;
- Leachate testing with deionised water and analysis of the leachate for major ions and trace elements;

- Particle size distribution;
- Moisture content; and
- Unsaturated hydraulic conductivity at various suctions.

Numerical modeling was conducted of geochemical and unsaturated flow processes within the tailings material.

Integration

The results of the hydrogeology and tailings drainage characterization were integrated into a generic conceptual model of the potential impact of tailings deposition into open pits.

3. RESULTS

Hydrogeology

Fifty-one boreholes were drilled in 2008 ranging from 7 m to 150 m in depth. Yields ranged up to 6 l/s with water strikes generally less than 45 m depth although one water strike was obtained at 118 m depth. The drilling confirmed the presence of water-bearing horizons in a shallow aquifer (up to 20 m depth) and intermediate aquifer (from approximately 23 m to 45 m). Aquifer development below 50 m is limited to discrete localised fracturing with no lateral continuity.

The piezometric head distribution in the shallow aquifer indicates a local northeast-southwest trending watershed through central Kimberley with groundwater flow directions to the north and south. The piezometric gradient is of the order of 0.007 and correlates strongly with surface gradients. The intermediate aquifer follows a similar trend in flow directions. The deep aquifer does not display groundwater gradients in any specific direction due to the irregular groundwater occurrence controlled by localised fracturing.

The dewatering of the mine pits displays a relatively small impact on water levels in the shallow and intermediate aquifers in terms of its radius of influence. A small cone of depression is noted around the Wesselton pit in the shallow aquifer.

Aquifer testing to assess the hydraulic parameters of the three aquifers yielded the results in Table 2.

Table 2. Aquifer parameters.

Aquifer	**Hydraulic conductivity (m/day)**	**Hydraulic conductivity (m/s)**	**Transmissivity (m^2/day)**
Shallow	0.4	4.6×10^{-6}	300
Intermediate	0.2	2.3×10^{-6}	100
Deep	0.09	10^{-6}	1

Groundwater Quality

A total of 21 groundwater samples were collected from the shallow aquifer. The water quality in the shallow aquifer is poor and is saline due to high concentrations of Mg, SO_4, Cl and Ca. The pH of shallow groundwater ranges from 6.7 to 8.5.

Groundwater sampling and analysis indicated that the shallow aquifer is characterised by an elevated salt load manifesting as high concentrations of SO_4. Two distinct zones of contaminated groundwater were identified in the shallow aquifer related to the historical mining and tailings storage activities.

In the intermediate aquifer the contaminant plume shows only limited migration of contaminated groundwater from the source areas, presumably due to the combination of low permeability and flat groundwater gradient.

Three samples were collected from boreholes in the deep aquifer. The groundwater quality is poor to moderate with dissolved solids in excess of 900 mg/l. The pH of groundwater in the deep aquifer exceeds 9.

Tailings Drainage Quality

A total of 118 composite samples representing 35 tailings resources distributed across the Kimberley area were analysed. The mineralogy of 12 tailings samples was characterized by X-ray diffraction (Figure 1).

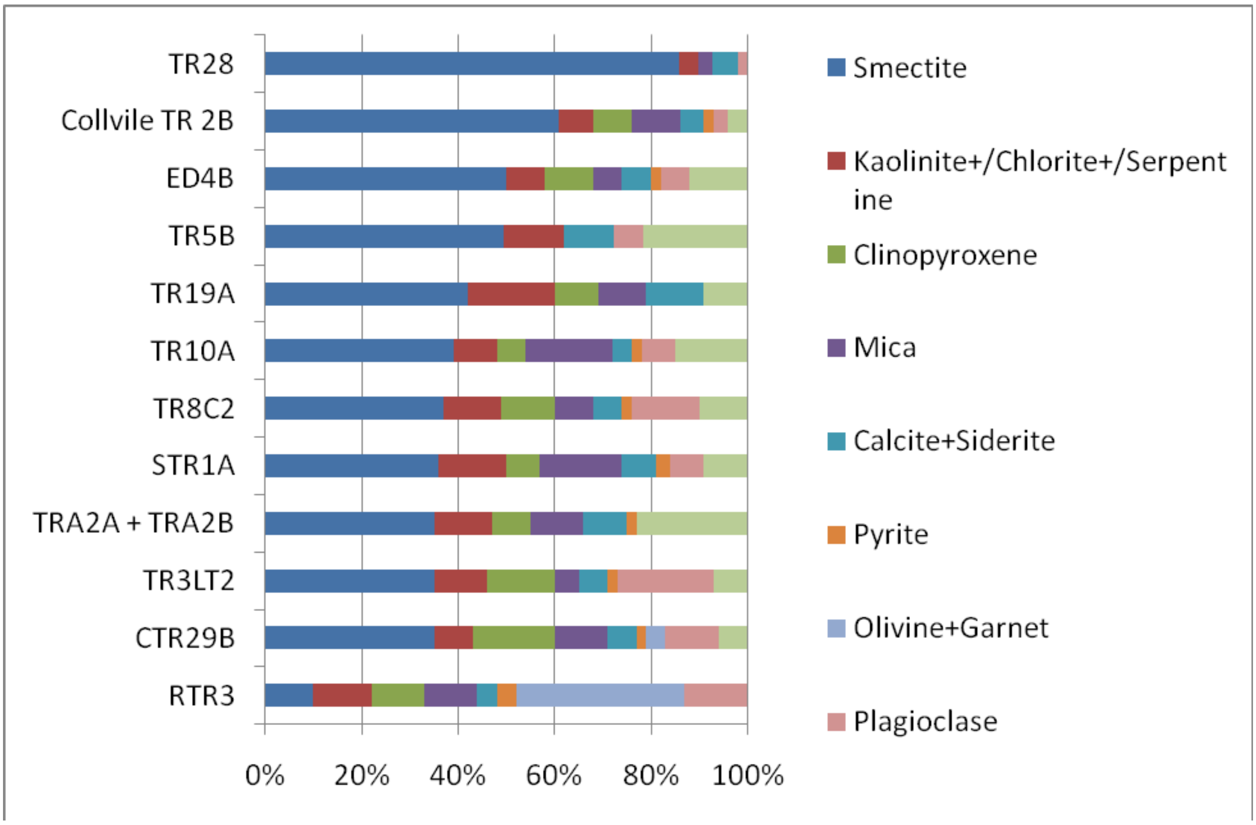

Figure 1. Tailings mineralogy

The mineralogical results indicate that the tailings composition is dominated by layered minerals including smectite, illite and chlorite. This implies that the tailings has a significant ion exchange capacity which may be expected to give rise to a highly variable drainage quality. This is consistent with the leach test results, as presented on a piper diagram (Figure 1).

The leachate from tailings is characterized by a very low proportion of chloride. The salinity of the leachate is dominated by Na-SO_4 and Na-HCO_3. While a significant number of tailings leachates indicate equilibrium with gypsum, and therefore suggest the influence of pyrite oxidation and neutralization processes in the tailings, the majority of leachate compositions plot in the central portion of the piper diagram (Figure 2). This suggests the influence of a number of geochemical processes such as weathering of less stable silicates such as olivine and the adsorption and desorption of cations on clay minerals. The wide variation in the hydrochemical signature of the tailings leachates reflects the wide variation in composition of the tailings.

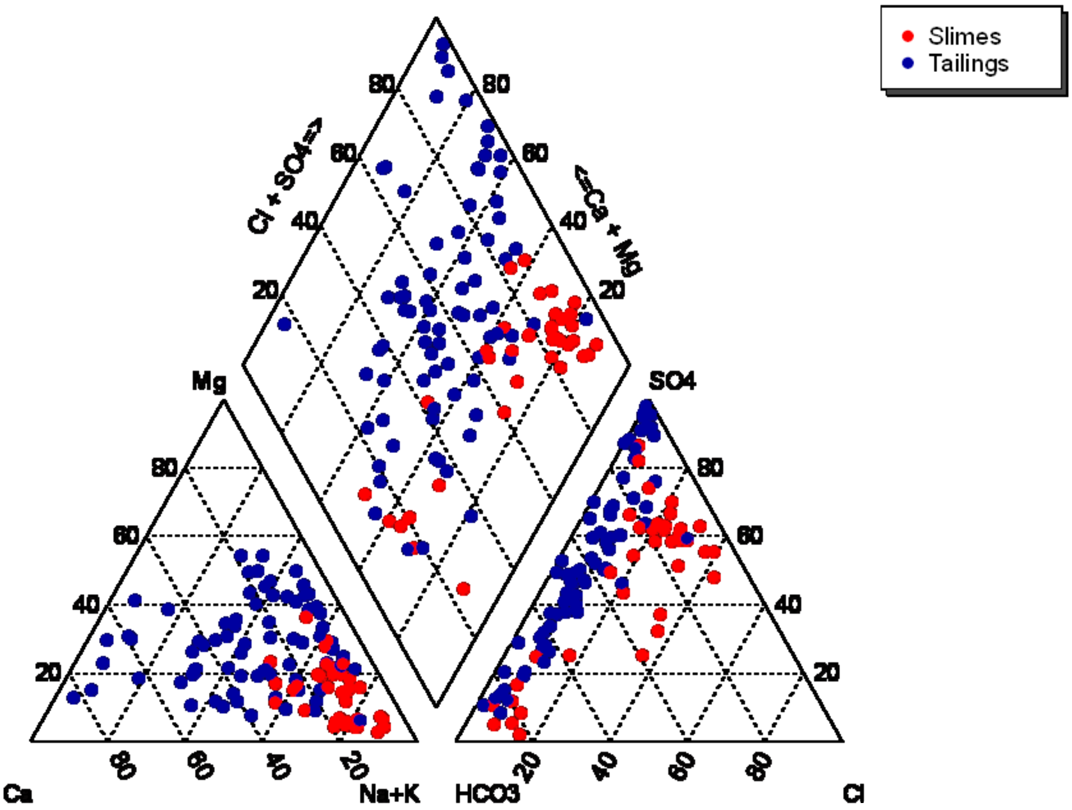

Figure 2. Tailings drainage quality, as assessed from short-term leachate testing.

Field observations indicated the presence of clay lenses in the tailings material (Figure 3). These clay lenses, apparently form at random in the material and may be laterally discontinuous. However, in places a near-surface "crust" forms consisting of tailings material cemented in a clayey matrix which apparently presents a surface that is resistant to erosion and water infiltration.

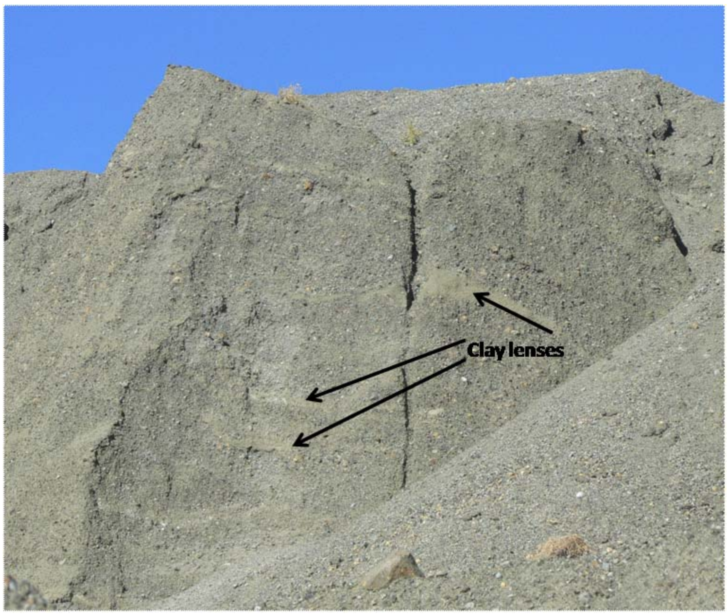

Figure 3. Occurrence of clay lenses in tailings material.

Based on particle size analyses, the Fredlund and Xing (1994) closed form solution was used to develop water retention curves for the tailings material (Figure 4).

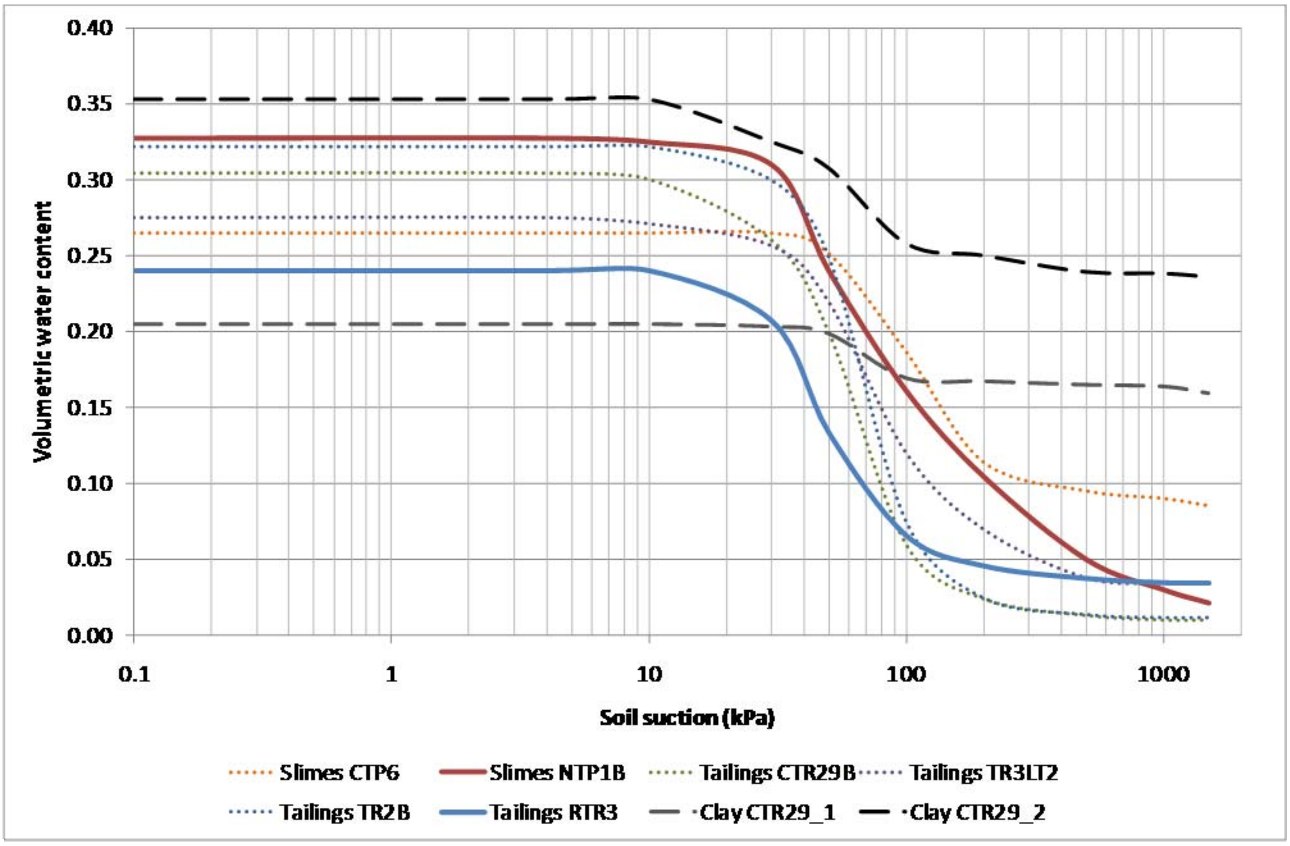

Figure 4. Water retentivities of tailings, as determined from particle size analysis.

The slopes of the retention curves are similar for the tailings, but the slopes of the clay lenses are flatter which indicates an adversity to the release of water. The residual water content of the clay lenses is high indicating that the water content will stay high (that is, negligible desaturation will occur) even under increased suction.

4. CONCEPTUAL MODEL

Tailings comprise between 10% and 85% smectite based on the analyses in this study. According to Vietti (2003) 50 % to 90 % of the clay mineral fraction in Kimberlite ore is from the smectite group. This is consistent with the 45% to 95% indicated from this study.

Smectite is a group of swelling clay minerals made up of 2:1 unit layers, each layer consisting of two silicon-oxygen tetrahedral sheets enclosing one Aluminium-oxygen (or hydroxyl) octahedral sheet. The layers are continuous in the horizontal directions and stacked one above the other in the vertical direction. Cations that are large on account of hydration (e.g. Ca^{2+}) are situated between the 2: 1 unit layers. Water and other polar molecules can enter between the unit layers causing the lattice to expand in the vertical direction (Van der Watt and van Rooyen, 1995). Vietti (2003) mentions that swelling may continue until normal electrical double layers separate individual clay particles.

The smectite characteristics result in a high water retention in the tailings. Water can be absorbed until the clay particles disperse, causing clay and fine particles to move downward in the profile and accumulate as clay lenses. Based on the properties determined from this study, the clay lenses form almost impermeable barriers to water movement. Therefore the permeability of the tailings is extremely variable.

The limiting factor to seepage rates in tailings is therefore the permeability of the clay lenses.

Pit Backfilling

Initially the water level in the pit will be well below the surrounding groundwater level and flow will be towards the pit. Tailings backfilled into the pit will equilibrate with the pit water forming a saline, sulphate-rich interstitial water. However, water infiltrating the top surface of the tailings will result in dispersion of the smectite. The tailings material will be enclosed and the dispersion of smectite will result in downward mobilization of clay particles rather than erosion of the tailings material. In the absence of erosion, it can be assumed that extensive and thick layers of low permeability clay will form and vertical flow will be limited. Movement of water within the backfilled tailings will therefore be limited to lateral, sub-horizontal flow.

Based on the results of the hydrogeological component of the study, the permeability of the country rock surrounding the pit is generally higher than the tailings permeability.

Rock permeability is generally higher than 10^{-6} m/s. Tailings permeability ranges from 10^{-9} m/s to 10^{-6} m/s. This will tend to limit groundwater flow through the tailings plugging the pit.

5. CONCLUSIONS

Currently tailings resources are scattered on the surface throughout Kimberley giving rise to widespread contamination of the shallow groundwater aquifer. The tailings contain a high proportion of smectite clays. Dispersion of the smectite can give rise to low permeability layers which can significantly restrict vertical infiltration. However, at surface, smectite dispersion also gives rise to erosion of the tailings which can limit the effect of low permeability layers. This results in mobilization of tailings drainage into the shallow groundwater system. The aquifer permeability is highest near surface.

If tailings are backfilled into a pit, they are enclosed and the development of low permeability layers will not be limited by erosion. In this environment the surrounding aquifer permeability is higher than the tailings. This will cause most groundwater flow to be diverted around the backfilled pits. The rate of leaching of salinity from the tailings is therefore likely to be several orders of magnitude lower than the current situation at surface. Based on the results of the hydrogeological, geochemical and unsaturated flow characterization of the tailings material, backfilling of reprocessed tailings is likely to have a beneficial impact on local groundwater quality in the long-term.

6. REFERENCES

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