



Feasibility of tailings retreatment to unlock value and create environmental sustainability of the Louis Moore tailings dump near Giyani, South Africa

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Synopsis

The reprocessing of tailings resources to extract gold on an industrial scale has become common practice. While these projects are common in the Witwatersrand basin, similar low-technology processes are not operational in smaller goldfields. This study explores the possibility of reclaiming the tailings dump of the Louis Moore Mine in the Giyani Greenstone Belt, investigates potential hazards to communities in the vicinity, and identifies mitigation strategies.

Auger samples were taken from the Louis Moore tailings at depths of up to 5 m. Aqua regia leach analyses show Au concentrations of up to 1 g/t. Inferred estimations based on ordinary kriging (OK) and inverse distance weighted (IDW) methods put the residual Au resource in the Louis Moore tailings dump at 0.20 t.

Reworking the tailings is viable, although a potential environmental risk exists in the form of elevated arsenic concentrations. Further exploration is required to determine the mineralogical associations of Au and As. Tailings reworking would assist in raising funds for mine rehabilitation. The secondary tailings could potentially be repurposed, which would provide employment and facilitate community development, as well as deliver environmental benefits.

Keywords

Louis Moore, tailings, gold, safety and health.

Introduction

The tailings retreatment sector in South Africa has been receiving a lot of attention due to the economic, environmental, financial, and political imperatives impacting new and existing tailings facilities. Blake (2013) asserts that some mining houses are exploring the unlocking of revenue in old tailings facilities because of the increasing cost of deep level mining, including operations with low recoveries (Sabbagha, 1982). The increase in commodity prices (Daniel and Downing, 2011) has led to the realization of retreating tailings. In most cases, extraction (>90%) has been by means of bioleaching (Carmen *et al.*, 2017; Ahmadi *et al.*, 2015). Bio-processing these waste materials has economic as well as environmental benefits (Bryan *et al.*, 2006).

The Louis Moore Mine is an abandoned underground mine, situated in the Ka-Mavalane village, about 10 km north of the town of Giyani along the road leading to Malamulele in Limpopo Province. Tailings constitute the only significant mine residue at the site. This study assesses the environmental hazards associated with these tailings and explores the economic potential of reclaiming gold.

Environmental hazards associated with this type of deposit are potentially high levels of arsenic (As) from arsenopyrite, which is normally associated with Au in shear zone-hosted Au deposits in Archean greenstone belts (Ward, 1999), as well as acid mine drainage (AMD) and its associated metal content (Alpers *et al.*, 1994). The economic potential is strongly dependent on the Au content. To assess risk and economic potential, the Louis Moore tailings were systematically sampled by auger, and geochemical analysis, mineralogical studies, and resource modelling undertaken to determine the potential of reworking the tailings.

Geological setting

The Giyani Greenstone Belt (GGB, formerly known as the Sutherland Greenstone belt) is situated at the northern edge of the Kaapvaal Craton. Its northwestern boundary defines the contact with the high-grade metamorphic Limpopo Belt (McCourt and van Reenen, 1992; Carranza, Sadeghi, and Billay,

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2014; Kramers, Henzen, and Steidle, 2014), with multiple shear zones developed along this contact. The now defunct Klein Letaba, Franke, Gembok, and Fumani mines are examples of Au deposits developed along such shear zones (McCourt and van Reenen, 1992; Gan and van Reenen, 1996).

The Louis Moore Mine is not situated in the main greenstone belt, but in a small greenstone belt remnant in the high-grade metamorphic gneisses to the north. Owing to poor outcrop conditions, no accurate geological map exists (Billay, Sadeghi, and Carranza, 2014). In the immediate surroundings of the Louis Moore Mine, banded gneissic rocks and micaceous schists occur, and foliation has a general east-west strike and a northerly dip. The Louis Moore orebody is hosted in tremolite schist, amphibolite, and granitoid gneiss, and is associated with quartz veins (Lombard, 1956). However, in comparison with other Au mineralization in the region and from the sparse outcrop mapping, it is likely that the orebody is associated with shear zones (Gan and van Reenen, 1996).

Material and methods

Drilling and sampling

Exploratory drilling using a traditional hand auger was carried out on the dump (which measures about 100 × 200 m) in November and December 2015. Holes were drilled to a maximum depth of 5 m, and material from every metre depth interval was split to yield a representative sample. This resulted in a total of 47 samples (less than 50, as some holes reached the base of the tailings at less than 5 m depth).

Sample analysis

The main analytical work was conducted at the University of Johannesburg (UJ) using ICP-OES as part of a multi-element analysis on sample leaches. Cross-checks were carried out by the Société Générale de Surveillance (SGS) Johannesburg laboratory; X-ray fluorescence (XRF) was used on pressed powders, while fire assay was used for Au. Twenty samples were further analysed using quadrupole ICP-MS at UJ for Au and uranium (U) for verification. X-ray diffraction (XRD) analysis was carried out on four samples by the Council for Geoscience, Pretoria, to assess the mineral content.

For the ICP-OES and ICP-MS analyses at UJ, aqua regia extraction was used, as per ISO 11466 of 1995. Aqua regia (20 ml) was added to 3.0 g of a dry tailings sample in a glass beaker. After being stored overnight at room temperature (allowing for slow oxidation of organic matter), the samples were boiled under reflux for two hours at a maximum temperature of 125°C. After cooling, the solution was filtered, evaporated to dryness, and re-dissolved to yield 100 ml of 1 M nitric acid,

which was stored. For analysis of major and trace elements by ICP-OES and ICP-MS, a further 1/10 dissolution was done and samples were analysed from a 0.3 M nitric acid solution. The instruments used included a SPECTRO® analytical instrument, ARCOS ICP-OES, and a Perkin Elmer® NexIon® 300 series quadrupole ICP-MS.

The pH values of slurries of sample material in deionized water were measured after being left to equilibrate overnight. Since the probes of pH meters are very sensitive and can easily be contaminated by particulates, comprehensive and user-friendly pH (pH-Fix 0-14) colour indicator strips (also called dip-in-read-off) were used to measure pH.

Statistical analysis and modelling

In order to understand element distribution patterns in the tailings dump, the analytical data was statistically evaluated. Inverse distance weighted (IDW) and ordinary kriging (OK) methods were trialled. Vulcan™ 3D software version 9.1.7 was used to model dump solids and surfaces, followed by block model estimation.

Results and discussion

pH of tailings

The Louis Moore Mine tailings have pH values ranging from 7 to 9, averaging 8. The neutral to weak basic conditions throughout the tailings dump can be attributed to the presence of dolomite (primarily associated with the mineralization) in the tailings. Residual lime used in pH adjustment during cyanidation may contribute to these values as well. While this means that no AMD currently emanates from these tailings, the overall alkaline chemistry is not optimal for plant growth as the availability of nutrients for uptake could be limited.

Mineralogical investigations on tailings

The XRD analysis results of four tailings samples, which were selected randomly, are shown in Table I. Mineralogical analyses on tailings by means of XRD are expected to show primary and secondary mineral occurrences. Primary minerals are ore and gangue minerals that were processed and deposited as tailings without any changes or alteration (Jambor, 1994). Secondary mineral phases are those that have been produced by processes that can lead to precipitation (Alpers *et al.*, 1994; Novhe *et al.*, 2014) and therefore formed after the tailings were deposited.

Tailings from the Louis Moore Mine have a variable, mostly high, quartz content. There are significant to abundant concentrations of dolomite, amphibole, serpentine, mica, and smectite minerals in samples KSG1D, KSG2D, and KSG3B. These minerals are absent in KSG5D, which contains plagioclase

Table I

XRD analysis of selected Louis Moore Mine tailings samples (wt. %)

Sample	Dolomite	Gypsum	Talc/pyrophyllite	Clinopyroxene	Ilmenite	Amphibole	Serpentine	Plagioclase	Quartz	Clinochlore	Mica	Smectite
KSG1D	20	–	–	7	3	35	3	4	15	–	5	7
KSG2D	5	2	2	–	–	31	2	–	30	5	16	7
KSG3B	43	–	2	–	4	23	6	–	8	–	5	8
KSG5D	–	–	–	–	–	tc	–	13	51	33	2	–

Notes:
(-) Not detected
(tc) Trace

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and clinoclone (Table I). It appears that different gangue assemblages and/or wallrocks were encountered at different times during mining. Generally, the mineral content reflects a mixture of country rocks typical of greenstone belt lithologies and granodiorite intrusions. The significant dolomite component is somewhat surprising and may reflect a carbonatization process related to ore emplacement, as found elsewhere in GGB Au deposits (Gan and van Reenen, 1996). Pyrrhotite or pyrite were not detected by XRD in the Louis Moore tailings but may be present in small amounts. The absence of jarosite, which is commonly associated with AMD, also attests to a low sulphide content in the past. The mineralogy is in accordance with the neutral to mildly alkaline pH values observed.

Contaminative elements assessment summary

Concentration data for elements of interest in terms of value or environmental hazard is listed in Table II. This section focuses mainly on the negative impacts of elements. Arsenic can cause cancer, nervous system damage, as well as skin, lung, liver, and heart damage. Chromium (Cr) is carcinogenic in the soluble hexavalent state. Copper (Cu) and nickel (Ni) are non-cumulative when ingested, but large doses of Cu can cause digestion and kidney problems, while Ni inhalation can cause respiratory problems and even cancer. Lead (Pb) is a cumulative toxin and particularly affects brain and nervous system development in children. High levels of U emit radioactivity, which is a serious problem with tailings from the Witwatersrand gold mines. If inhaled, U causes damage to lungs, and after entering the bloodstream, the absorbed uranium tends to bio-accumulate and remain for many years in bone tissues (Glaser, Hippel, and Frank, 2006). Very high uranium intakes (50 to 150 mg) can cause acute kidney failure and death. At lower intake levels (25 to 40 mg), damage can be seen by the presence of protein and dead cells in the urine. It is important to note that kidneys repair themselves over a period of 8 weeks after uranium exposure has ceased, but only if the intake was at low levels (WHO, 2000).

The Louis Moore tailings do not show U concentrations above normal uncontaminated soil levels (1–2 µg/g). They contain significant concentrations of the metalloid As (mean 277 µg/g) and contaminative metals Cr, Cu, Ni, Pb, and zinc (Zn). The average values for Cd and Pb are within allowable limits for soils. Those for Cu and Zn exceed target values for soils only

slightly, while concentrations of Cr, Ni, and particularly As, are well above South African and international soil target values. The concentration of As in natural soil ranges from 1 to 40 µg/g.

While in most of the boreholes As concentrations are below detection levels from bottom to top, three boreholes have high As levels over their complete depth, and one has high levels at 1–2 m only. Thus, while there does not seem to be a vertical zonation of As, there is a very irregular horizontal distribution. Arsenic is fairly well correlated with P, and high P (526.95 µg/g) levels are found in the same boreholes that also have high As contents. Under oxidizing conditions, As and P are present in solution as the arsenate (AsO_4^{3-}) and phosphide (PO_4^{3-}) oxyanions, respectively, which are both adsorbed on, and co-precipitated with, Fe oxides and hydroxides, although this tendency is stronger for arsenate than for phosphate (Strawn, 2018).

Under moderately reducing conditions, As is present as the arsenate (AsO_5^{3-}) ion, which is not adsorbed on Fe oxides, while P remains as the phosphate ion (Strawn, 2018). Thus, the correlation of P with As indicates that (a) conditions were oxidizing, and (b) both elements were in solution during sedimentation of the tailings. This could have led to localized concentrations of both elements in the tailings. Borehole KSG5 (one of the sites with high As and P concentrations over the whole depth) contained stagnant water during sampling. If this was a low point during deposition of the tailings, it might have led to local concentration of dissolved As and P which then became fixed by adsorption. Arsenic is immobile in soils under neutral and slightly acidic conditions (Blowes *et al.*, 2003), but can be mobilized at pH < 2 or > 9 (Gersztyn, Karczewska, and Gałka, 2013). Although the pH values up to 9 found in the tailings are very marginal to the conditions for As mobilization, potentially high levels of As in the groundwater around Louis Moore Mine are a concern. Communities are discouraged from residing or working on or adjacent to these tailings, since the dust blown from them could still be rich in As.

Cu, Ni, Pb, and Zn would be released as cations under natural leaching conditions. The leaching of these elements from the tailings and their mobility in groundwater is expected to be very low at neutral pH, increasing somewhat at pH values > 9 as $\text{Cu}(\text{OH})_2$, $\text{Pb}(\text{OH})_2$, $\text{Ni}(\text{OH})_2$ and $\text{Zn}(\text{OH})_2$ complexes are formed. Furthermore, Cr when oxidized to Cr^{6+} is highly mobile at high

Table II

Summary of contents of elements of interest (µg/g)

	As ⁽¹⁾	Au ⁽²⁾	Cd ⁽²⁾	Cr	Fe	P ⁽¹⁾	P	Ni	Pb	U ⁽³⁾	Zn
No. of samples	47	47	47	47	47	47	47	47	47	15	47
Minimum	0.00	0.00	0.00	69.0	0.00	23710	0.00	43.16	0.00	1.09	25.23
Maximum	2151	0.94	0.8	727	134.5	82661	526.9	459.74	87.52	1.33	128.03
Range	2151	0.94	0.8	658	134.5	58950	526.9	416.58	87.52	0.24	102.80
Mean	277	0.37	0.4	359	40.47	51191	113.8	224.39	26.88	1.15	69.79
Median	0.00	0.39	0.00	389	16.60	53062	0.00	204.64	29.00	1.14	68.81
Standard deviation	456	0.25	0.3	190	39.70	13736	161.1	116.41	25.00	0.06	24.53
Detection limit	8.3	0.08	0.8	5.4	3.3	8.3	11.7	8.3	10.0	0.01	8.3
WHO limits (soil)	40	n/a	0.8	100	36	n/a	n/a	35	85	n/a	50

Notes:

- Arsenic was detected in only 16 samples from just 4 boreholes (see Figure. 1). The mean As concentration for the samples in which As was detected is $724 \pm 456 \mu\text{g/g}$ (1 SD). Phosphorus (P) was detected in all 18 samples from these boreholes; the mean P concentration being $255 \pm 148 \mu\text{g/g}$ (1 SD).
- Cadmium (Cd) was not observed above the detection limit of 0.8 µg/g, which is listed as the maximum concentration.
- Au analyses were checked by ICP-MS (15 samples selected randomly) which confirmed the ICP-OES data. U could not be analysed by ICP-OES due to interference of an iron (Fe) line, and 15 samples were analysed by ICP-MS.

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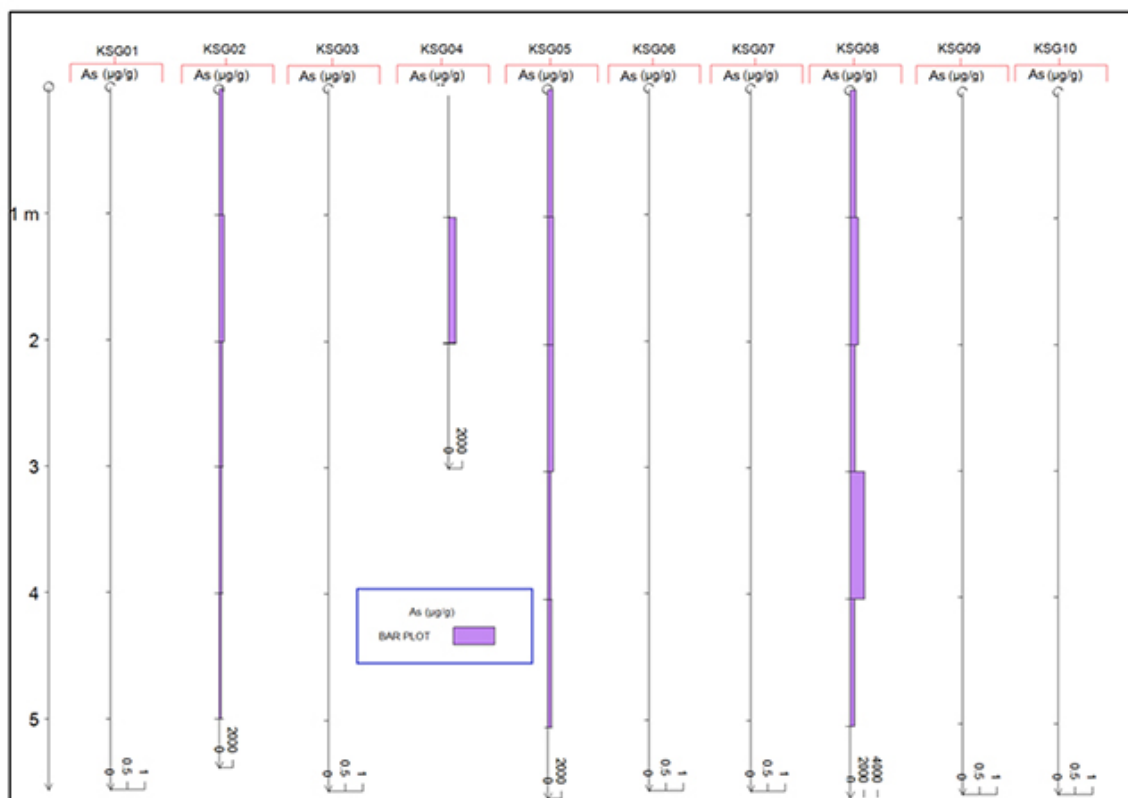


Figure 1 – Strip log showing As concentrations and distribution in all boreholes

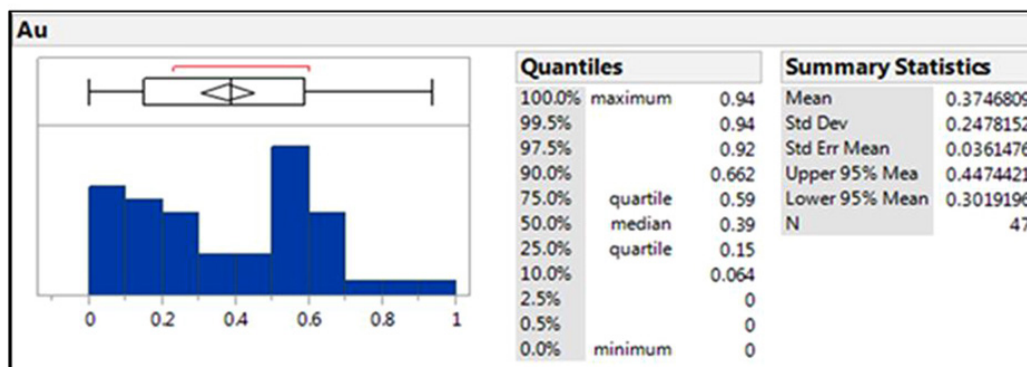


Figure 2—Histogram of Au distribution

pH, which could possibly be a serious environmental concern in the surroundings of the Louis Moore tailings (van der Sloot and van Zomeren, 2012). However, the Cr in the tailings is most likely hosted in silicates and oxides (notably chromite). Although this Cr was oxidized and dissolved in the aqua regia leach, chromite would be stable in natural weathering processes.

Distribution of Au in auger holes

During drilling a general homogeneity and lack of distinct layering was observed in the tailings. Generally, in all ten holes, the effects of dumping season and fluctuating mining operations are evident. Given the apparent lack of mobility for Au (and other trace elements), these factors are the main cause of variation in concentrations. In all drilled holes, Au concentrations are high (up to 1 ppm), which is attributed to poor plant recovery efficiency during mining. These concentrations require a formal geometallurgical study to help assess the economic feasibility of

extracting Au, with a view to re-treating the tailings, which, in turn, will assist in cleaning up the environment and allowing the land to be further developed. The histogram for Au data shown in Figure 2 presents an even and random (non-skewed and non-normal) distribution of concentrations.

A tailings dump is not a natural deposit geologically formed *in situ*, and the deposition of Au in it is not controlled by geological processes of ore deposit formation. To draw a solid conclusion when working with tailings is therefore very difficult. Although this is not the subject of this section, it is worth noting that no significant systematic enrichment or depletion with depth has been noted for most trace and major elements analysed in this study. Generally, the random variation of Au values indicates the effects of dumping season and fluctuating mining operations, as well as variations in the ore grade encountered during mining. This presents a positive outlook for further exploration and exploitation.

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Modelling (block model development) and grade estimation

Survey points (shown in red in Figure 3) were used to model the top surface of the dump together with drill-hole collars (shown in green). Bottom strings digitized from end-of-hole points were used to model the floor or base. The top and bottom surfaces of the Louis Moore Mine dump were appended to form a 3D closed solid on which the block model design was based, and which serves to estimate the volume of the tailings dump for an estimate of the total gold content.

Block model design

Two block models were created for the entire tailings dump area, which included the upper and bottom surfaces as constraints. Air blocks outside dump domains were deleted to optimize block model size and ensure that no air blocks outside the dump triangulations were estimated. Block models were validated by visual inspection and creating diagonal sections across dump domains. For visualization purposes, the tailings dump was exaggerated ten times in the Z dimension. This was done because the 5 m drill-holes resulted in dense Z extents on the block model. This exaggeration does not change the extents of the block and triangulation models; it is solely for the purpose of visualization.

Visual validation

Visual validation was performed by viewing cross-sections and comparisons of the grade in the block model to the sample

database. The correlation between the sample grades and the block model is good.

In order to check for potential biases in the block model grade estimate, the IDW block grades were compared to the OK estimation at a zero cut-off grade. OK estimation provides one of the best estimates of the mean grade of a tailings because the drill-hole sample data is declustered. In Figure 5, the two grade models are compared, and it can be seen that they provide a very similar prognosis for tonnage to be mined as a function of the cut-off grade.

Estimation of the total Au resource within the tailings dump

No density measurements were conducted in the UJ laboratory on tailings samples. The tonnage calculated is based on densities obtained from the previous studies and laboratory tests. South Africa's Witwatersrand gold ores have densities ranging from 2.74 kg/m³ to 2.77 kg/m³, based on calculations for rocks containing 94% silica with accessory pyrite. The density of greenstone schists and gneissic rocks, on the other hand, varies between 2.6 and 2.9 kg/m³. The banded iron formation (BIF) records 3.6 kg/m³ (Hacto Corp, 2011). As such, a density of 1.4 kg/m³ for the Louis Moore tailings dump was assumed.

The total tonnage of tailings material was used to deduce the total amounts of the various elements. The total area for the Louis Moore Mine tailings dump is 4.3 ha (43 000 m²) and the volume is 387 000 m³. The average density is 1.4 kg/m³. No geological losses (dykes, sills or even washouts) were included

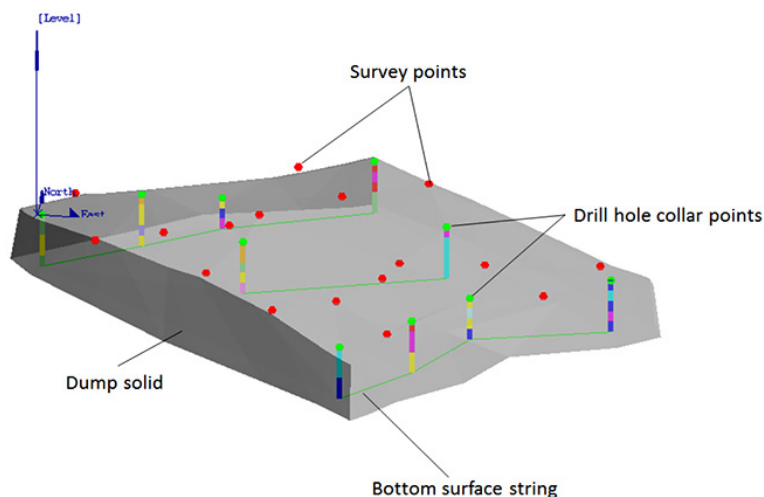


Figure 3—A starting basin showing solid modelled surfaces for the topography of the Louis Moore tailings dump (grey surface indicates tailings)

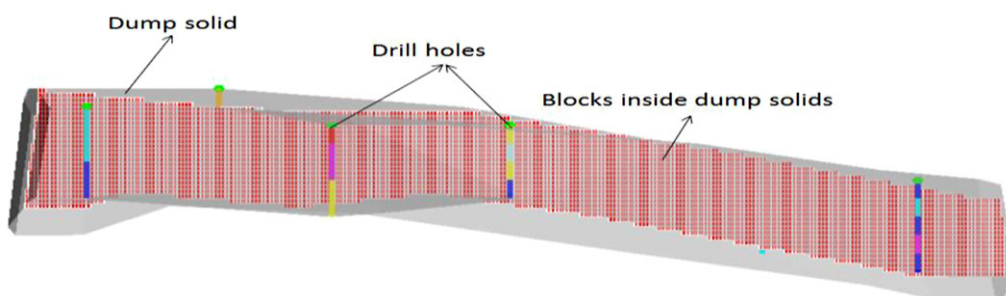


Figure 4—Barren (un-estimated) Louis Moore Mine tailings dump block model section before grade estimation, exaggerated in the Z dimension by 10x to view the blocks section

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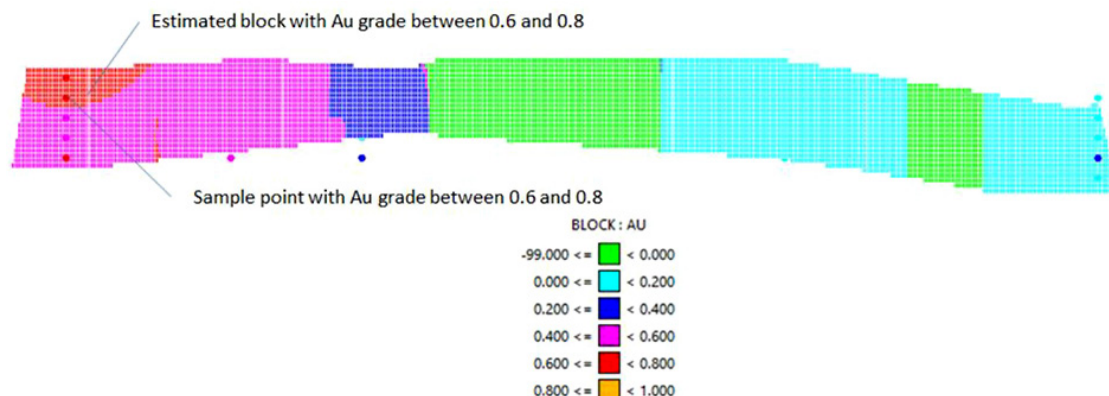


Figure 5—Typical block model cross-section of Au grades. W-E section showing Au sample data and block model estimates of the Louis Moore Mine tailings dump

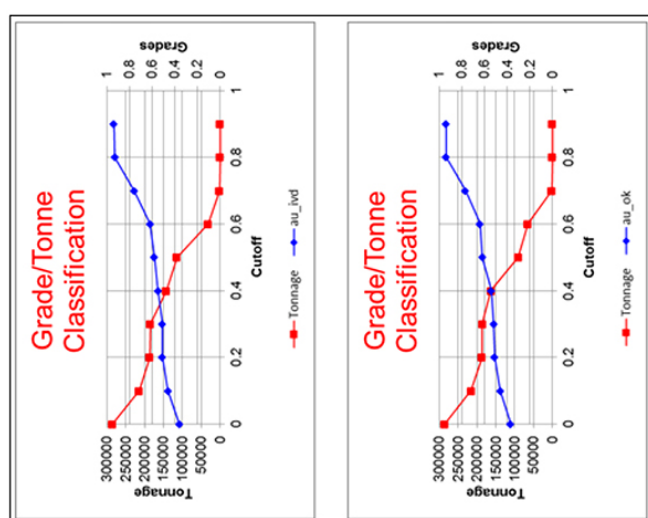


Figure 6—The Louis Moore Mine tailings dump grade/tonnage report for gold, comparing OK (au_ok) and IVD (au_ivd) estimation

in the mineral resource estimation, as there should not be any structure present in the dump that will cause losses and a 100% reclamation of the dump is assumed (thus corresponding to a cut-off grade of zero in Figure 5 and complete removal of the dump). Taking the mean Au concentration from Table II (0.000037%), the total metal tonnage (T , in metric tons) is derived from the volume (V , in m^3), the density (ρ , in t/m^3) and the grade (C , in %) as $T = V \times \rho \times C/100 = 387\,000 \times 1.4 \times 0.000037/100 = 0.20\,t$ (assuming 100% recovery).

Conclusion

Conclusions from the data reported in this study relate to (a) environmental and health risk, and (b) potential Au exploitability. There is no indication of AMD emanating from the tailings (pH values range from 7 to 9), but a potential health risk is presented by As, which could be mobilized under mildly alkaline conditions and contaminate soils and groundwater. It is unlikely that groundwater has been contaminated with heavy metals; the pH of the tailings is insufficiently high to mobilize Cu, Ni, Pb, and Zn as OH complexes. While Cr^{6+} could be mobile, the stability of its host mineral phases probably prevented its liberation. The main risk is associated with the possible inhalation or ingestion of dust by residents of the nearby community. Any remedial measures

should include stabilizing the dump surface (slope stabilization), e.g., by vegetation to prevent loose soil from being blown or washed away) or engineered covers comprising a water-saturated clay liner to minimize oxygen ingress, thus reducing oxidation rates. Communities living in affected areas could be relocated, but intervention measures requiring a relatively small budget, such as fencing to limit open access to the tailings by humans and animals, are recommended.

The Au resource enhances the economic viability of an environmentally beneficial surface retreatment project. Further exploitation of this dump using simple technology is proposed; for example, sluice guns could be used to mine the dump and limit dust generation. The site is located 200 m away from a perennial river, which could (assuming a water use licence is granted) serve as a source of water. Reclamation of the mined dump can then follow to mitigate further environmental challenges.

Ultimately, all feasibility studies on future land use must consider the possibilities for proper rehabilitation of these areas, following the removal of the physical obstacles to development, and see to it that they are developed to their full potential. The main aim is to extract the residual minerals. Following extraction of the valuable metals, the following potential land uses should be considered.

Power generation or urban development: The tailings dump covers a large area of land and is elevated, and hence would be a suitable site for wind turbines or a solar (photovoltaic) energy farm. Being in the tropics, solar radiation is intense. The tailings are less than 500 m from the village, which makes it inexpensive and easy to connect power lines. Alternatively, if the dump can be reclaimed and all toxic metals extracted, the area could be used for village extension.

Heritage site: The Louis Moore mines are over 100 years old and qualify to be declared heritage sites in terms of the National Heritage Resource Act, 1999 (Act No. 25 of 1999) under Section 32 (5) (b) (i).

Academic and industrial research potential: Due to the complexity of the tailings, geometallurgical studies must be undertaken before deciding on the viability of reworking, presenting opportunities for further research. Geology and mining engineering students could use these sites as case studies. This study has revealed a number of geological and mineralogical issues that can be further investigated in detail.

Community development projects: Tailings materials have similar mechanical properties to the clay used in the brick and tile

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industry. The option of making bricks and tiles will lead to jobs being created in the re-mining/retreatment process, along with training/skills transfer to the local community. It is important to use materials with that low heavy metal concentrations to avoid contamination of land and water or possible adverse health effects for occupants of dwellings built using contaminated material.

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