8. Uranium migration in gold tailings disposal facilities

8.1 Introduction

The geochemical nature of U allows high mobility and transportation in oxidised gold tailings. This is a major environmental hazard and needs to be studied further for both quantification and mitigation of potential pollution resulting from gold TDFs (Aswathanarayana, 1985). As the mobility of U is dependent on a number of environmental parameters including pH, eH, anions and cations (Section 2.5), this section compares concentration relationships in order to quantify and visualise the change in U concentration, irrespective of the cause of mobilisation.

8.2 Objectives and motivation

This section proposes to quantify the migration of U within a TDF. It suggests the use of a U migration index in order to aid in modelling and graphical representation of the transportation of U. The detail of sampling allows lateral and vertical modelling of migration in a 3D graphical environment.

Quantification and modelling of U migration in gold tailings may assist in resource planning during re-mining, as well as prevention of environmental contamination.

8.3 Estimating migration of uranium

The persistence of Th under oxidizing conditions allows Th to be used as a reference concentration in order to evaluate the original U concentration, prior to the formation of an oxidizing environment (Aswathanarayana, 1985). As the ratio of U/Th is constant in the same rock type (Asfahani *et al.* 2007., Aswathanarayana, 1985), it can be inferred that the ratio of U/Th should be constant in the tailings produced from the same rock type as long as U was not mined together with gold. Since no U mining was done at New Machavie, this assumption is valid; however, the mobilisation of Th (as seen in previous chapters) does occur although significantly lower than U. Th mobilisation will increase the error margin of U mobilisation modelling by using the U/Th ratio in the oxidized zone. Due to the extremely long half-lives of Th and U the current U/Th ratio can be assumed to be the original U/Th ratio when the rock units were deposited as long as oxidation of U has not occurred (Asfahani *et al.* 2007). The NMA Internal Scientific Report (1999) states that the U migration value (Um) can be attained by subtracting the original U concentration (Uo) from the currently measured U concentration (Uc).

$$Um = Uo - Uc \qquad (5)$$

The NMA Internal Scientific Report (1999) also states that the original U concentration (Uo) can be determined from the U/Th ratio of the geological unit according to the following equation:

$$Uo = eTh \times (unit\ eU/eTh) \qquad (6)$$

Where eTh is the measured Th content (ppm) and unit eU/eTh is the average ratio of U to Th in the geological unit as a whole. As data regarding the original unit eU/eTh for Black Reef Formation ore was not attainable, the average unit eU/eTh for the New Machavie tailings was calculated from downhole probing data. Equations 5 and 6 were then used to calculate the normalised migration rate (Um%) of U as follows:

Um% = (Um/Uc) x 100 ***(7)***

NMA (1999), Asfahani *et al.* (2007) and Assran *et al.* (2012) stated that negative Um% values indicated movement of U out of the region, whilst positive Um% indicated movement into a region. Upon careful consideration, it was found that this was erroneous and that negative values indicated movement into a region rather than out of a region. Table 8.1 indicates the rationale behind this statement with 2 examples; one with increased U content as the result of U migration into a region, and one with U migration out of a region. Table 8.1 also includes the Th content and the different indices as mentioned in equations *(5)*, *(6)* and *(7)*. The Um% can be used as a measure of the direction of U migration since positive values indicate migration out of a region, whilst negative values will indicate migration into a region.

Table 8.1: Calculation of Um%

Variable	**Mobilisation away from region**	**Mobilisation into region**	**Remarks**
Uc	4.7	9.5	Currently measured U content in ppm
Th c	1.5	1.5	Currently measured Th content in ppm
U/Th	5.07	5.07	Unit U/Th ratio as calculated from the whole unit
Uo [*eTh x (unit eU/eTh)]*	7.6	7.6	Original U content as calculated from equation *(6)*
Um [*Uo – Uc*]	2.9	-1.9	U migration value as calculated from equation *(5)*
Um% [*(Um/Uc) x 100*]	61.8%	-19.95%	U migration rate as calculated from equation *(7)*
	Positive Um% is attained from areas where U was decreased relative to Th.	Negative Um% is attained where U was increased relative to Th.	

Despite this discrepancy in the literature, the Um% can be considered a valuable variable in the assessment of U migration and should not be disregarded.

8.4 Methodology

The results of the down-hole probing were used to calculate the Um% of each measured data point (± 2 cm interval for each borehole). The down-hole results were used as these showed the best statistical correlations and the least variation from the ICP-MS results, and therefore were deemed more reliable.

The Um% values were modelled using a strong directional-influenced IDW to interpolate individual voxel values. The model was constrained to the stratigraphic model as described under Section 4.8.

8.5 Results

The modelling of the Um% is indicated in Figure 8.1 and Appendix D. In the 3D modelling images, high values on the scale (100 - 300) represent high mobility of U and do not reflect concentration of U. Inversely negative values indicate.

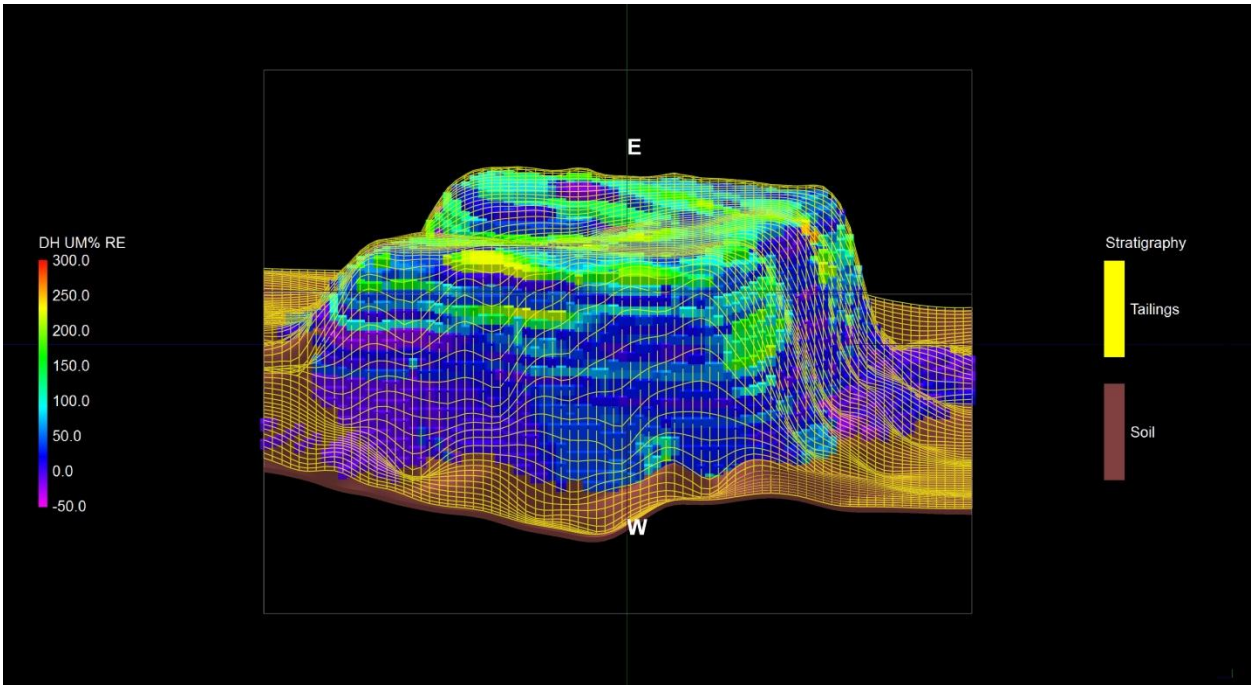

Figure 8.1: West-east view of Um% at New Machavie

The 3D images (Appendix D) indicate that there has been mobilisation of U from the top of New Machavie (high values) to the lower regions (low values). This has occurred across the TDF

with some localised variations. The largest accumulation occurred at the south-eastern corner as indicated in Figure D.1 and D.3 (Appendix D). In Appendix D, Figures D.6 to D.21 show vertical profiles of the Um% modelling along profile lines as indicated in Figure D5. In all of the profiles, U has shown mobilisation from the top of the TDF to the lower portion. U has this strong mobilisation pattern due to the geochemical nature of both the tailings material and U where mobilisation of U is increased under oxidised conditions. The top portions of the TDF are exposed to air and water, which create a strongly oxidised environment where pyrite is oxidised and results in very low pH conditions and abundant sulphate anions (Bezuidenhout & Rousseau, 2005., Yibas et al., 2010). Uranium found in this oxidized zone will oxidize to a U6+ state where the uranyl ion will complex with sulphate anions to produce highly mobile UO2SO4 and UO2(SO4)2- species (Vandenhove et al., 2009., Pulford, 2010., Alloway, 2012). Large areas of the TDF still show the signature of the original U/Th ratio (indicated as dark blue or Um% range of 0 – 40). These areas are yet to be mobilised and accumulation has not occurred.

The depositional environment of gold tailings produces layers where particle size differential settlement occurs. Layers of fine tailings followed by layers of courser tailings occur throughout the TDF (Robertson, 2008). These fine layers usually act as a buffer that reduces oxygen penetration, as well as regulating the hydraulic properties by preventing water ingress or providing water through capillary action. Fine-grained layers also tend to remain wet for longer periods than the layers with courser particles since adsorption forces between fine-grained particles and water are stronger due to negatively charged broken crystal faces (a result of the milling process) (Hillel, 2004). This reduces the oxidative properties of the tailings and prevents U from being mobilised. Further study is needed to include particle size distribution into the modelling of U migration.

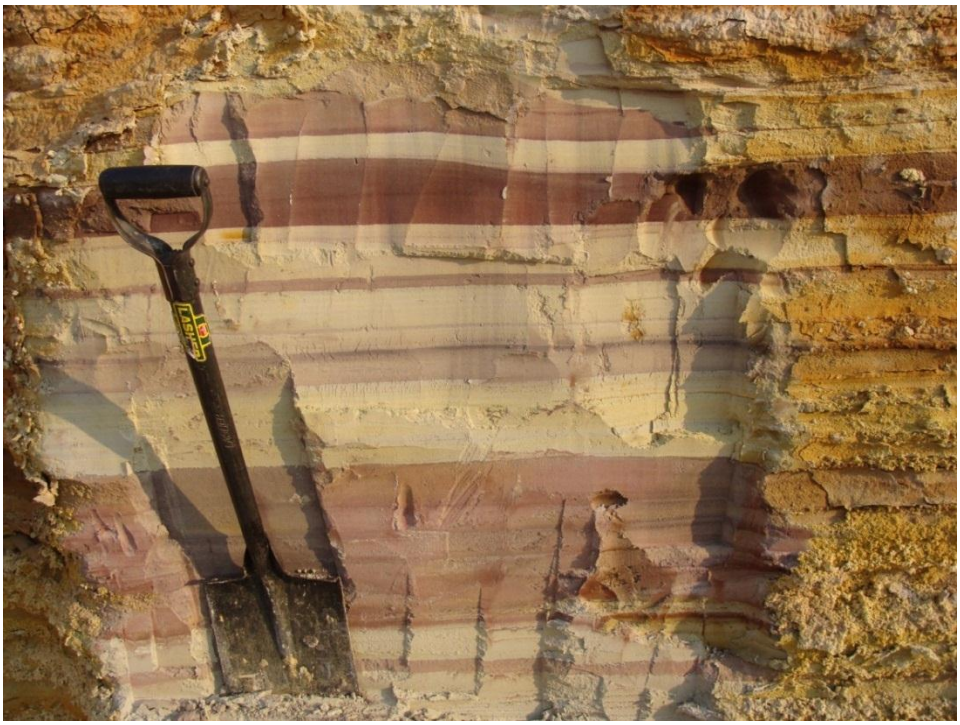

Photo 8.1: Layering in gold tailings

The physical prevention of water ingress also prevents U from being mobilised to lower parts of the TDF. Capillary rise of water may account for some U being transported upwards instead of downwards although this effect is very low and not easy to pinpoint in the profiles. Figures D.6, D.9, D.11, and D.13 to D.17 indicate that blue layers are generally part of a succession of layers, where U has been transported away from one layer into another layer. Vandenhove *et al.* (2009) and Pulford (2010) indicated that U has an adsorption affinity for oxides, clays and phosphates, where negatively charged particles adsorb U chemical species and thus decrease mobility. As the fine-grained layers have greater adsorption charges, this acts as adsorption sites to decrease mobilisation of U. Figure 8.2 highlights this succession of layers, where red arrows indicate transportation direction.

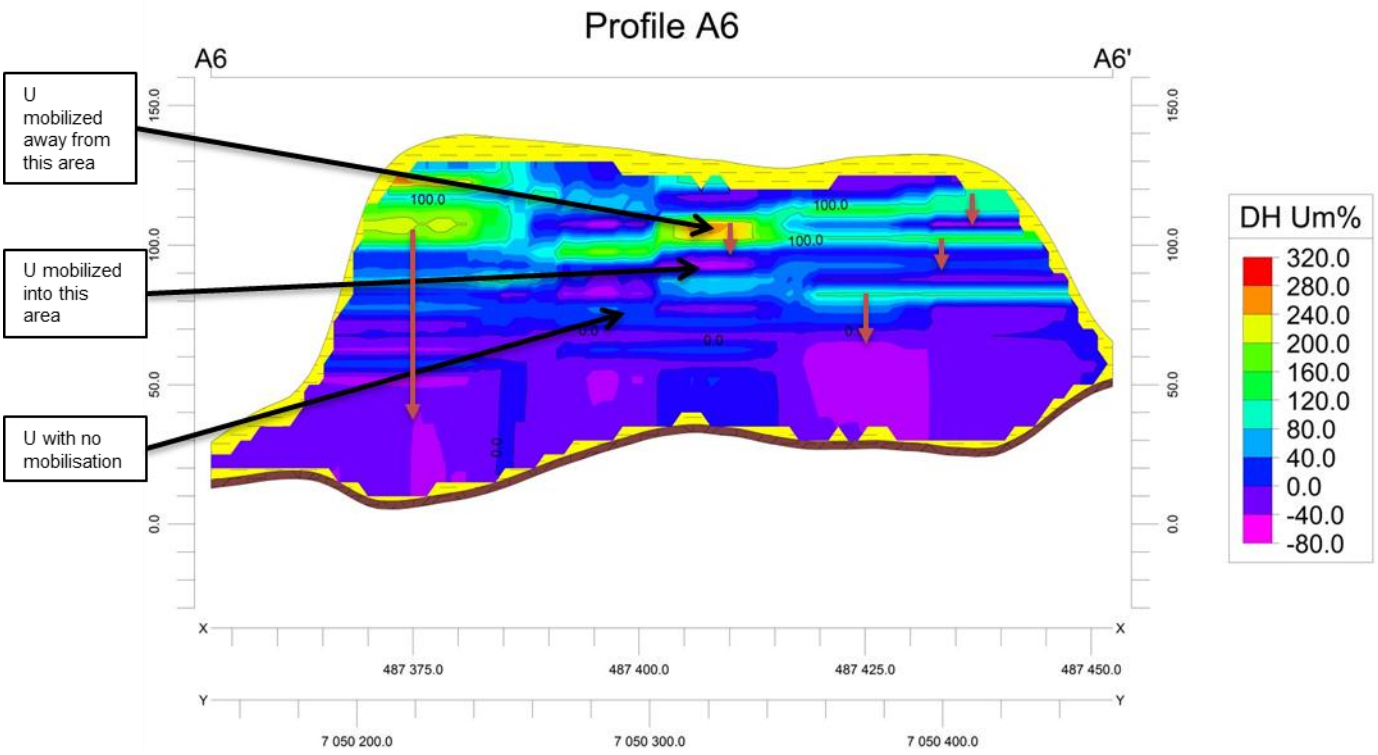

Figure 8.2. Profile through New Machevie indicating the succession of mobilised and un-mobilised layers

Theoretically, layers with a very fine particle size tend to accumulate water above the layer until a flow path can be found to a lower level. This accumulation of water with mobilised U is indicated as purple layers just above a blue layer. The area where U has been mobilised will then be a green to red layer above the purple layer. This is an ideal situation and in reality is much more complex since layers tend to pinch out and particle sizes have both horizontal and vertical variations. The general trend remains, accumulation occurs lower in the TDF whilst mobilisation and transport away from the upper portions is the norm.

Figures D.6, D.8, D.16, D.17 and D.18 show some strong vertical features. These features are a region where transportation has occurred along a vertical pathway to the bottom of the TDF. This may suggest that the underlying bedrock has a flow pathway in this area that accepts the fluid from the TDF and transports if away from the TDF into the groundwater. Figure D.20 on the other hand shows a vertical accumulation feature which has to be investigated further in order to specify the reason that vertical accumulation has occurred.

8.6 Conclusion

The Um% was able to quantify the mobilisation of U within the New Machavie TDF. There is definitive transportation of U from the top of the TDF to the lower portions of the TDF, as well as away from the TDF in all directions, although the main transportation direction is south-east along the natural drainage direction of the study area. Particle size effects on the hydraulic flow of fluids within the TDF also affect the mobilisation and deposition of U within the TDF at different layers, and needs to be studied further. Transportation of U may also occur within the TDF along preferential flow pathways, reflecting the influence of the underlain bedrock which accepts fluid ingress.