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In-depth lithological and weathering profile of a waste rock dump

Mélanie St-Arnault, Maria Eliana Lorca, Bern Klein, K. Ulrich Mayer, Roger D. Beckie
University of British Columbia, Vancouver, Canada

ABSTRACT

Over the past ten years, the weathering mechanisms of waste rock at the Antamina Cu-Zn-Mo mine in Peru have been investigated. Recently a rotary vibratory drilling program was performed at two locations in the waste dump. The drill program presented a unique opportunity to gather mineralogical and geochemical information and to study the evolution of the alteration profile through time and depth associated with observed lithologies (e.g. skarns, intrusives, marbles, hornfels). The waste dump under investigation is approximately 400m tall with material that is highly heterogeneous in composition and grain size.

A previous study showed that the reactivity of minerals vary with depth within the same borehole, because of variations in pore water chemistry and gas transport. The relationship between the variation in reactivity, the lithology, and the alteration profile is investigated in this study. The results provide information on the heterogeneity of the material in the waste dump. The observation of reactivity compared with lithology from the drill hole highlights the potential presence of complex geochemical mechanisms such as galvanic reaction and secondary mineral precipitation. The results will guide future research and demonstrate the contribution of weathering mechanisms on the long term release of metals from waste rock piles.

Key Words**:** neutral rock drainage, metal leaching, weathering mechanisms, attenuation and release of metals, secondary minerals

1 INTRODUCTION

Drilling in waste rock piles presents the opportunity to characterize the interior structure and composition of waste rock dumps (Sracek et al. 2006). In general, end dumped waste rock piles show heterogeneity of grain size distribution, surface compaction and lithological composition. Former studies have recognized the importance of the physical and chemical heterogeneities on the reactivity of the waste rock materials (Amos et al. 2014; Stockwell et al. 2006; Lefebvre et al. 2001). The material reactivity can be assessed by the presence of sulfide mineral oxidation and secondary mineralization observed within the waste rock dump. The oxidation reactions consume oxygen and generate heat, therefore the reactivity can be monitored by following the fluctuation of oxygen and temperature within the borehole. The reactivity of minerals vary with depth within the borehole in association with the migration pattern of pore water and gas transport forming reactive hotspots (Lorca et al. 2015).

2 SITE DESCRIPTION

Antamina is a polymetallic copper (Cu), zinc (Zn) and molybdenum (Mo) mine. The skarn deposit is located in Peru at an elevation between 4000m and 5000m above sea level. The typical annual precipitation is between 1200mm and 1500mm with average temperatures of 5.4 to 8.5 ºC (Harrison et al. 2012). There are three major waste rock types identified at the mine: carbonates (i.e. limestone, marble, hornfels), skarn (i.e. endoskarn and exoskarn) and intrusive (Harrison et al. 2012).

Recently a rotary vibratory drilling program was performed in the East dump presented in Figure 1. The sonic drill provided continuous core samples and information along two boreholes BH1D2 and BH3D2. Hence, the drill program presented a unique opportunity to gather mineralogical and geochemical in situ information (e.g. gas, temperature, acid base accounting, sulfide and secondary mineral content, or moisture content) associated with specific lithological intervals along the borehole.

Figure 1 Borehole location on the East Dump at Antamina.

The East waste dump is approximately 400m tall with material that is highly heterogeneous in composition and grain size. The dump is composed of alternating lithological layers of skarn, intrusive, marble and hornfel and the most recent material is located at the top of the dump and the oldest material deposited at the base of the dump is approximately ten years old. BH1D2 was drilled on the upper part of the dump, whereas BH3D2 was drilled on a lower part of the dump. The BH1D2 waste rock has been exposed to weathering for a shorter period of time because it was deposited after the BH3D2 material. Boreholes BH1D2 and BH3D2 were drilled a few meters away from BH1s, BH3s, and BH3d boreholes drilled with reverse circulation air rotary in 2012 on the same sites. Gas transport and temperature data are available from those boreholes (Lorca et al. 2015).

3 OBJECTIVE

The purpose of this study is to assess the degree of heterogeneity between and with depth within the boreholes. An investigation of the variation in reactivity, the lithology and the alteration profile within the two boreholes of 126m and 146m located at the proximity of the dump' slope was performed.

4 METHODOLOGY

A composite sample was taken for each lithological interval identified by Antamina's geologists from boreholes BH1D2 and BH3D2. The lithological identification was done by visual observation based on the occurrence of rock fragments being superior or inferior to 50%.

The samples collected were analyzed for gravimetric moisture content, neutralization and acid potential, and solid phase elemental content. The moisture content was evaluated in each sampling interval by weighing 500g to 1 kg of material, before and after being dried in the oven according to the ASTM procedure D2216-10 (ASTM, 2010). Static tests, ICP-MS, ICP-OES analyses were performed on selected samples by the ALS laboratory in Lima.

5 RESULTS

5.1 Lithology

Figures 2 and 3 show the distributions of the main lithological units observed in BH1D2 and BH3D2 boreholes. The BH1D2 samples are composed of 58% of carbonate rocks, 29% of a combination of 50% skarn or Intrusive and 50% carbonate rocks, and 13% skarn, intrusive or a combination of skarn and intrusive. Comparatively, BH3D2 samples are composed of 34% of carbonate rocks, 54% of a combination of 50% skarn or Intrusive and 50% carbonate rocks, and 12% of skarn, intrusive or a combination of skarn and intrusive.

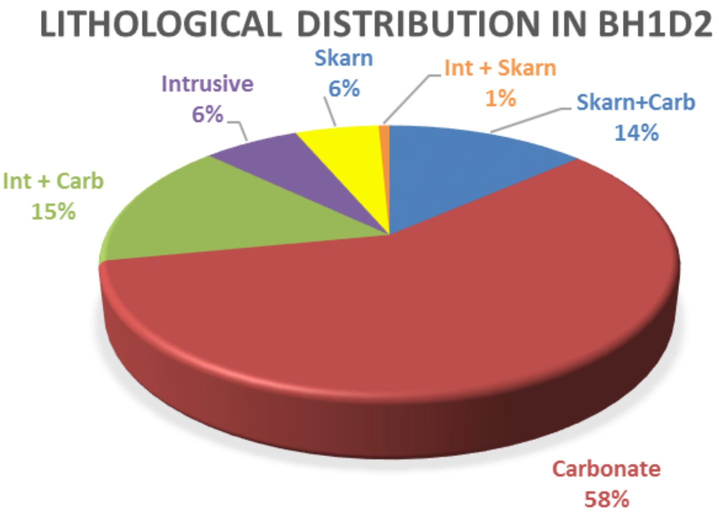


Figure 2 Distribution of main lithology or lithological combination observed in borehole BH1D2

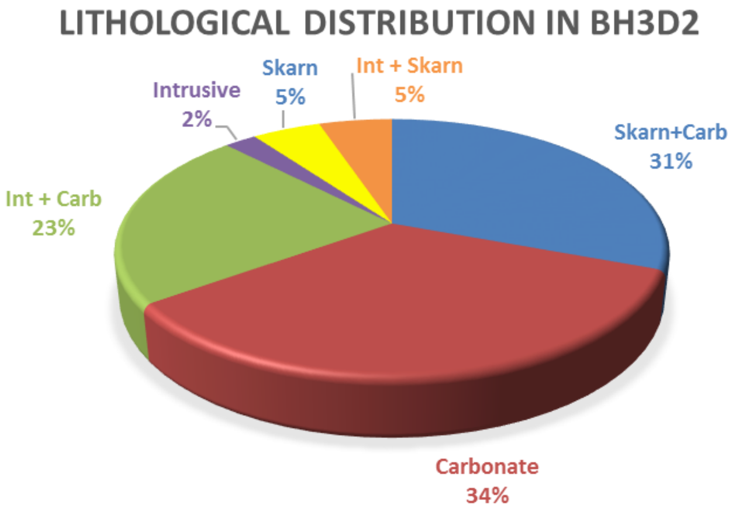


Figure 3 Distribution of main lithology or lithological combination observed in borehole BH3D2.

5.2 *Reactivity*

Results from the previous boreholes BH1s and BH3d located adjacent to BH1D2 and BH3D2, respectively were compared to investigate what could be the cause of reactivity. Results from BH1s show that this borehole has a higher temperature and oxygen depletion between 10m and 20m compared with results from BH3d (Lorca et al., 2015). The data for BH1d are only available from 0m to 20m, so it was not possible to compare the reactivity with the remaining of BH1D2 beyond 20m. The lower portion of BH3d shows two zones with increased temperature and oxygen depletion from a depth of 30m to 45m, and from 80m to 100m depths.

5.3 *Solid Phase Analysis*

The total sulfur and metal contents show higher heterogeneity at depth and between the two boreholes. The average content of total sulfur for BH1D2 is 0.9% with a maximum of 3.9 %, and an average of 1% with a maximum of 19% for BH3D2 similar to that reported by Lorca (2015) for the adjacent boreholes. In both boreholes, Zn and Cu are the most abundant metals followed by lead (Pb), Mo, and Arsenic (As). BH1D2 shows higher concentrations of: Zn at 75m to 110m and 130m to 141m depth; Iron (Fe) between 90 m to 110 m, and at 142m; and Cu between 75m to 100m. BH3D2 shows higher concentration interval of: Zn between 0m to 30m, 40m to 45m, 80m to 90m, as well as 105m and 125m; Fe between 0m to 30 m, and 60m to 70m; Cu between 0m to 30m, 50m to 70m, and 85m to 90m; as well as Mo from 50m to 85m.

5.4 Alteration

15 to 20% sulfide content was estimated to be disseminated in the matrix of the core samples at 35m, 85m and 100m in BH3D2 and 7-15% between 20 to 40 m and 60m in BH1D2. Peaks of iron oxide alteration are observed at 12m, 35m, 90m and 95m in BH3D2 and 20m, 40m and between 85m at 100m in BH1D2. Carbonate and sulfate alteration are observed between 20m and 50m and a peak at 90m with secondary copper alteration. For BH1D2 carbonate/sulfate and secondary copper is observed between 20m to 40m, and 70m to 100m.

5.5 Moisture

Figures 4 and 5 show the measured gravimetric moisture content for the two boreholes BH1D2 and BH3D2, respectively. The values range between 0.5% and 15% for both boreholes. Drops in moisture content are observed at 25m and 80m for BH3D2 and at 50m, and 104.8m for BH1D2.

6 DISCUSSION

6.1 Lithology and Alteration

The layers composed of mixed intrusive-carbonate and skarn-carbonate are the most abundant lithologies along drill hole BH3D2. Marble, Hornfels and Limestone carbonate rocks are the most abundant along the drill hole BH1D2. The presence of disseminated sulfides was observed in up to 25% of the matrix. Iron oxides, sulfates, carbonates, and malachite are some of the secondary phases observed in the waste rock matrix.

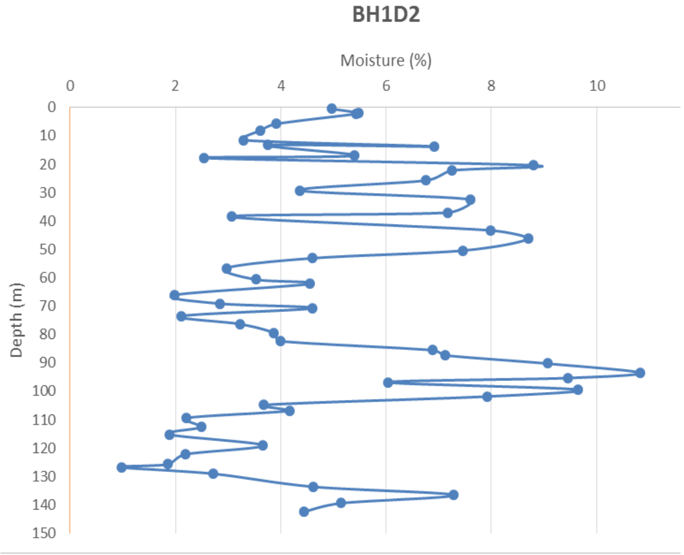


Figure 4 Gravimetric moisture content of the borehole BH1D2

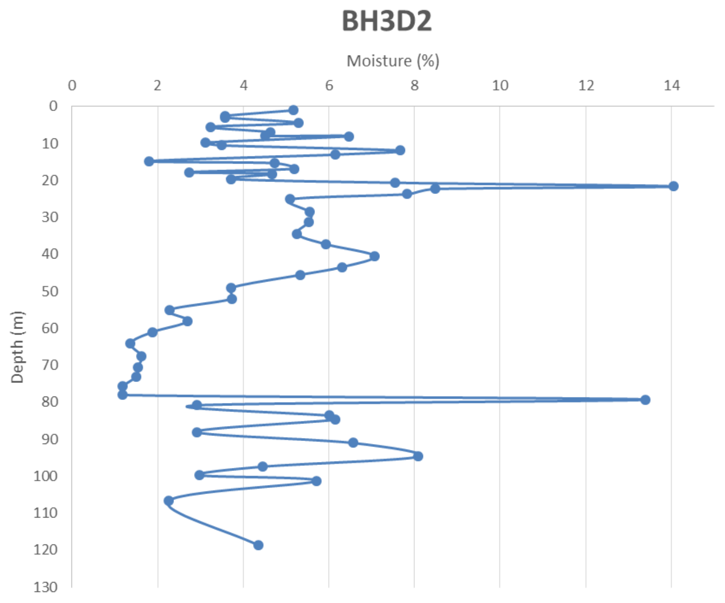
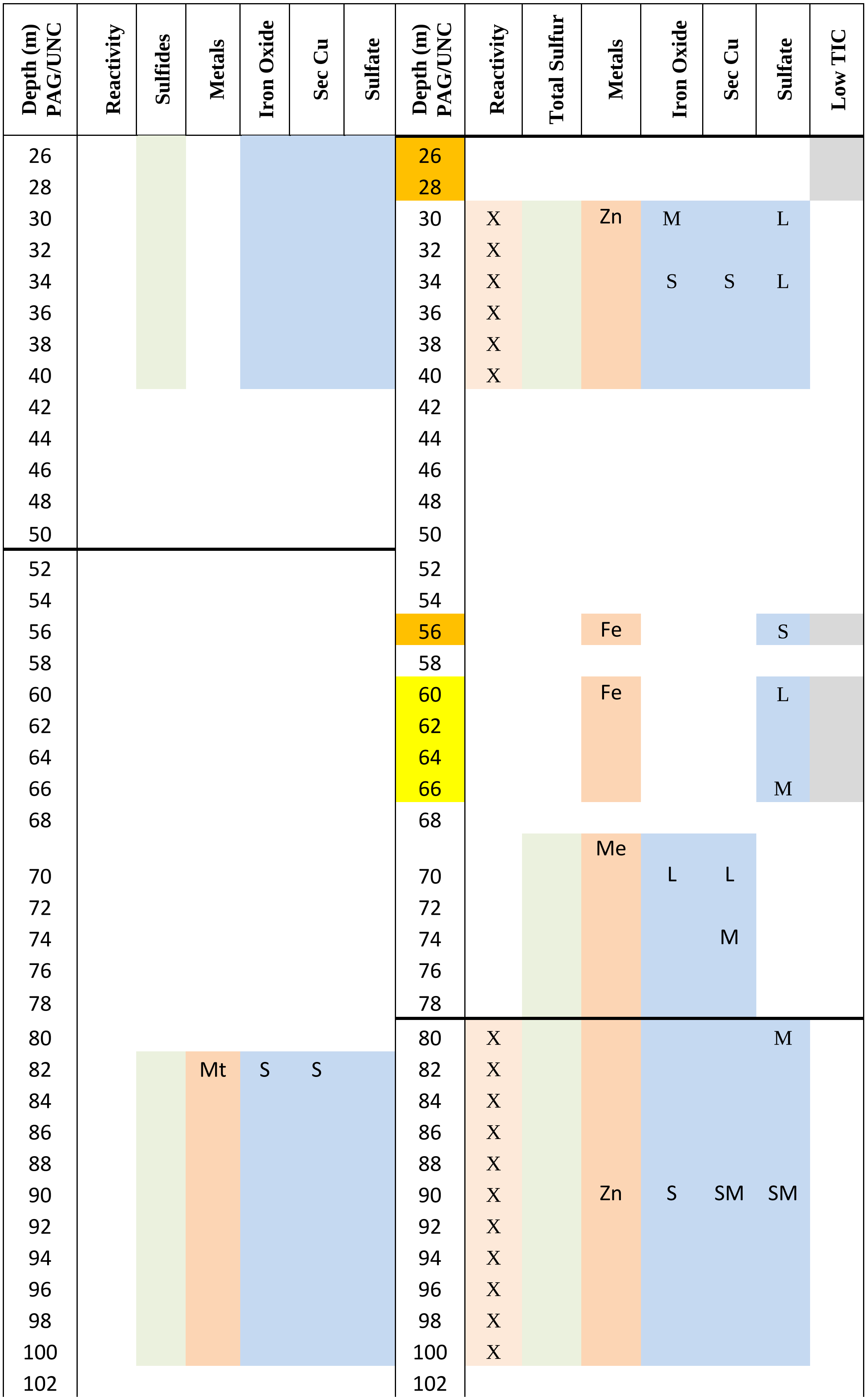


Figure 5 Gravimetric moisture content of the borehole BH3D2

The occurrence and intensity of alteration in the matrix between the two boreholes are similar despite high lithological heterogeneity and different location in the dump. The distribution of FeOx alteration with depth seems to follow a similar pattern between the boreholes displaying two to three main zones of alteration. Table 1 presents a summary of the main reactivity, solid phase content, moisture, and alteration zones in the matrix observed along BH3D2 and BH1D2.

Table 1 Main reactivity, moisture and alteration zones observed at depth along BH1D2 and BH3D2 (Sec Cu = Secondary copper carbonates, yellow = potentially acid generating (PAG), Orange = uncertain (UNC), Bold line = drop of moisture content, L = Low, M = Medium, S = Strong, TIC = Total Inorganic Carbon)

Depth (m) PAG/UNC	**Reactivity**	**Sulfides**	**Metals**	**Iron Oxide**	**Sec Cu**	**Sulfate**	**Depth (m) PAG/UNC**	**Reactivity**	**Total Sulfur**	**Metals**	**Iron Oxide**	**Sec Cu**	**Sulfate**	**Low TIC**
BH1D2							**BH3D2**							
2							2							
4							4							
6							6							
8							8							
10							10							
12							12							
14							14							
16	X						16							
18	X						18							
20	X			M	S	S	20							
22							22							
24							24							



Depth (m) PAG/UNC	Reactivity	Sulfides	Metals	Iron Oxide	Sec Cu	Sulfate	Depth (m) PAG/UNC	Reactivity	Total Sulfur	Metals	Iron Oxide	Sec Cu	Sulfate	Low TIC
26							26							
28							28							
30							30	X		Zn	M		L	
32							32	X						
34							34	X			S	S	L	
36							36	X						
38							38	X						
40							40	X						
42							42							
44							44							
46							46							
48							48							
50							50							
52							52							
54							54							
56							56			Fe			S	
58							58							
60							60			Fe			L	
62							62							
64							64							
66							66						M	
68							68							
										Me				
70							70				L	L		
72							72							
74							74					M		
76							76							
78							78							
80							80	X					M	
82			Mt	S	S		82	X						
84							84	X						
86							86	X						
88							88	X						
90							90	X		Zn	S	SM	SM	
92							92	X						
94							94	X						
96							96	X						
98							98	X						
100							100	X						
102							102							

Depth (m) PAG/UNC	Reactivity	Sulfides	Metals	Iron Oxide	Sec Cu	Sulfate
104						
106						
108						
110						
112						
114						
116						
118						
120						
122						
124						
126						
🟨 128						
130						
132						
134						
136						
138						
🟧 140						
142						

Depth (m) PAG/UNC	Reactivity	Total Sulfur	Metals	Iron Oxide	Sec Cu	Sulfate	Low TIC
104							
106							
108							
110							
112							
🟧 114			Zn				▨
116							
🟨 118			Zn				▨
🟧 120							
122							
124							
126							

Me: Pb, Zn, Cu, Mo

Mt: Fe, Zn, Cu

6.2 *Acid Base Accounting, Lithology, and Alteration*

The borehole BH1D2 only have the presence of one interval of PAG and UNC samples at 128m and 140m. In BH3D2 the presence of PAG and UNC intervals (e.g. 2.6m, 6m, 19m to 28m, 59.4m to 68.5m, 117m to 121m) are directly related to the presence of higher Fe solid phase content and low iron oxide (FeOx) alteration as well as low sulfide content observed in the matrix. They also show Total inorganic carbon values located in the lower quartile compared to solid phase sulfide (S2-) values located between the median-higher quartile. The two main lithologies associated with those intervals are carbonate rocks as well as a combination of skarn/intrusive and carbonate rocks. The BH3D2 PAG samples were most likely exposed for a longer period to weathering than BH1D2 samples, meaning that the buffering minerals are potentially depleted or passivated.

6.3 *Moisture*

Borehole BH3d intersects two main traffic surfaces between 65m to 70m and 110m to 115m which correspond to different bench heights. The traffic surfaces are typically composed of finer particle sizes and are compacted (Amos et al. 2014, Lefebvre et al. 2001). Lower temperature due to lower reactivity and coarser material were observed at the base of the lifts between benches (Lorca et al. 2015). Variation from lower to higher moisture content was observed at depths of 50m and 105m for BH1D2, as well as 25m and 80m for BH3D2. Hence, the moisture content variations observed could be related with traffic compacted material and/or the predominant presence of clayish material observed at those locations.

6.4 *Reactivity, Solid Phase Content and Lithology*

The reactive hotspots are associated with higher temperature and oxygen depletion (Lorca et al. 2015). The presence of reactive hotspots observed between 10m and 20m in BH1s corresponds to the presence of sulfide disseminated in the matrix of BH1D2 at 20 m. The main lithology observed is an interval of oxidised intrusive and skarn between 20m and 20.5m.

Similarly, the high reactivity intervals observed between 30m to 45m and 80m to 100m in BH3d correspond to higher sulfide contents in BH3D2 at intervals between 35m to 40m, at 85m and 100m. The main lithology within these intervals is a combination of intrusive/skarn and carbonate inter-layered with individual intrusive, skarn and carbonate layers. The presence of higher concentrations of Zn and Pb between 38m and 42m and the high Cu, Zn and Pb between 80m to 100m in BH3D2 could also be a source of metal released or attenuated by the reactions in those intervals.

BH1D2 is more reactive than BH3D2 at 20m because of its higher observed sulfide content in the matrix and the correlation made between the temperature and oxygen data taken from the adjacent hole BH1s as discussed in the Section on Reactivity above. However, FeOx staining has been qualitatively observed to be higher in BH3D2.

6.5 *Reactivity and Alteration profile*

The distribution of the FeOx alteration with depth follows a similar pattern within both boreholes. Both display occurrence of FeOx alteration between 0m to 15m, 30m to 40m, and 90m to 100m. This may be related to the grain size distribution and moisture content associated with the different waste rock dump benches.

The waste rock solid phase content and the traffic surfaces have a direct impact on the reactivity and alteration profile observed within the boreholes. No differences of intensity were noted between the alteration located at the top and bottom part of the two boreholes. However, higher reactivity is rising at the top of traffic surfaces in dump benches resulting in the presence of strong FeOx alteration lower in depth within the bench.

7 CONCLUSION

The drill program presented a unique opportunity to gather mineralogical and geochemical information (e.g. gas, temperature, acid base accounting, sulfide and secondary mineral content, or moisture content) along two boreholes covering an in-depth vertical section of approximately 150m per borehole. The continuous data set displayed the evolution of the alteration profile at depth associated with observed lithologies. The results highlight the relationship between reactive hotspots with the physical and geochemical heterogeneities.

The main conclusions from the information presented are:

- Weathering was expected to be more evident at the base of the boreholes. However, the alteration is located at the middle of each deposition benches following the distribution of the grain size in each bench.
- The reactivity is directly related to the presence of higher sulfide content but does not always correlate with higher FeOx alteration.
- The PAG and UNC intervals are mostly associated with the presence of combined lithologies and layers rich in carbonate rocks with a low TIC and Ca solid phase content. Meaning that the carbonates are potentially depleted or passivated in these intervals.

The results discussed provide information on the heterogeneity of the material in the waste dump. The observation of reactivity compared with lithology from the drill hole highlights the potential presence of alteration mechanisms. Amongst other, the presence of non-acid generating sulfides, complex geochemical mechanisms such as galvanic reaction between sulfide couples (Kwong, 2003), and secondary mineral precipitation at the surface of the carbonate or sulfide (Huminicki, 2008, Huminicki, 2009) might have an impact on the elemental release and attenuation, reactivity, and buffering potential of the waste rock. Further mineralogical investigations will be conducted during the next phases of this study using the samples collected in the drilling program, to assess the presence of these potential mechanisms and the impact on the geochemistry of the waste rock dump.

8 ACKNOWLEDGEMENT

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