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Investigation of Pore Gas Oxygen and Internal Temperature in a Waste Rock Dump, Antamina Mine, Peru

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ABSTRACT

Sulfide mineral oxidation in waste rock dumps tends to increase internal temperatures and may lead to oxygen depletion. The objective of this study is to address how waste rock heterogeneity affects dump-internal gas and temperature distributions. Waste rock dumps built by end dumping are characterized by a high degree of grain size segregation, where coarse rock fragments rest at the bottom, and smaller particles remain near the surface. Due to truck traffic, the fine-grained material located near the surface is compacted. In addition, chemical heterogeneity, in particular sulfide content, also affects internal reactivity and oxygen demand. A drilling program was initiated at Antamina to investigate pore gas and temperature distribution within one of the operating dumps. The investigated dump is 400 m tall and the material is geochemically highly heterogeneous, containing waste rock composed of skarn, hornfels, marbles and intrusives. Two sites where drilled: At Site 1 a shallow borehole was completed, and at Site 3 a shallow and a deep borehole were completed. The sulfur content of the drilled material showed a high degree of chemical heterogeneity with depth; the average sulfur content is 2.5%, but some of the intervals present sulfur content higher than 10%. A thermistor string and oxygen probes were inserted in the boreholes for monitoring of in-situ sulfide mineral oxidation. Areas of increased reactivity (elevated temperature and low pore gas oxygen) correspond to intervals of waste rock with high sulfur content. Regarding the overall reactivity, Site 1 is warmer than Site 3 and shows a higher degree of oxygen depletion. The nature of temperature and oxygen profiles in the deep borehole (Site 3) indicates the presence of reactive hotspots and complex pore gas and pore water migration patterns. These results highlight the role that physical and chemical heterogeneities have on waste rock reactivity.

Keywords: Waste Rock; Oxidation; Heterogeneity, Heat Generation

INTRODUCTION

In this study we investigate the effect of waste rock heterogeneity on dump-internal oxygen concentration and temperature distributions. Sulfide mineral oxidation in waste rock dumps increases internal temperatures, due to the exothermic nature of the sulfide mineral oxidation, and reduces oxygen concentration in the pore gas with respect to atmospheric levels.

Waste rock dumps built by end dumping are characterized by a high degree of grain size segregation, where coarse rock fragments rest at the bottom, and smaller particles remain near the surface (Smith and Beckie 2003; Amos et al. 2014). Due to truck traffic, the fine grained material located near the surface is compacted. (Lefebvre et al. 2001; Amos et al. 2014; Wels, Lefebvre, and Robertson 2003). Laboratory reactivity studies have shown that pyrite oxidation is higher with decreasing particle size (Stromberg and Banwart 1999; Hollings et al. 2001).

In addition, chemical heterogeneity, in particular sulfide content of the dump also affects internal reactivity and oxygen demand. Everything else being equal, zones of the dump where the sulfide minerals are abundant will present increased reactivity, elevated temperature and lower oxygen concentration.

The ingress of fresh air from the atmosphere brings oxygen to supply the reaction. This air can be drawn into the dump by advection/convection due to pressure and/or temperature gradients, but diffusion will also supply oxygen in presence of concentration gradients. Wels et al. (2003) provide an overview of gas flow in waste rock dumps. The main processes are depicted in Figure 1.

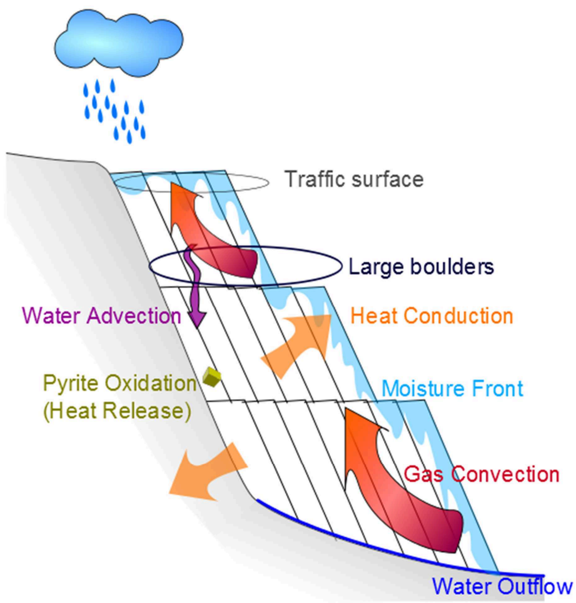

Figure 1 Conceptual model of the processes affecting oxygen transport within waste rock dumps.

Boreholes provide an opportunity to monitor the interior of waste dumps. Borehole construction is difficult and expensive, often limiting installation possibilities. In the past, some waste rock dumps and coal spoils have been successfully drilled, instrumented and monitored (Harries and Ritchie 1981; Lefebvre et al. 2001; Milczarek et al. 2009).

The traditional model of waste rock dump weathering considers that the oxidation processes occur in the exterior of the piles, whereas the interior stays oxygen deprived (Ritchie 2003). Numerical models show that bulk convection can occur in some dumps, where sulfide oxidation rates are high and permeability and diffusion are enhanced, allowing the ingress of oxygen deep into the dump.

METHODS

Site Description

The Antamina mine is located approximately 270 km northeast of Lima, Peru in the department of Ancash. It is located in the high Andes, at an elevation ranging between 4200 and 4700 m.a.s.l. There are two marked wet and dry seasons, the annual precipitation ranges between 1200 and 1500 mm, and the average annual temperature ranges between 5.4 and 8.5°C (Harrison et al. 2012).

Antamina is a polymetallic skarn deposit. It produces copper, zinc, and molybdenum concentrates, and silver and lead concentrates as by-products. The intrusion that produced the mineralization is hosted in sedimentary carbonate sequences (Love, Clark, and Glover 2004). There are five major lithologies in the mine: intrusive, skarn, hornfels, marble and limestone.

Drilling and Instrumentation

A drilling program was initiated at Antamina in conjunction with UBC to investigate pore gas and temperature distribution within one of the operational waste dumps. The investigated dump is 400 m tall and the material is geochemically highly heterogeneous, containing waste rock composed of skarn, hornfels, marbles and intrusives. A photograph of the dump with the location of the boreholes is shown in Figure 2. Two sites where drilled: At Site 1 a shallow borehole was completed, and at Site 3 a shallow and a deep borehole were completed 10 m apart from each other. The two sites are 1 km apart.

The boreholes were drilled with a percussion hammer (Casagrande C3 drill rig). The samples were retrieved by reverse air circulation using a cyclone, and there was neither use of drilling lubricants nor water. Casing was advanced using approximately 2 m lengths of welded steel casing. The percussion hammer breaks the rocks into smaller pieces therefore the particle size distribution of the samples is not representative of the deposit.

Solid phase analysis and ABA testing was done at ALS Peru. In this paper we present data on sulfur content. Analysis of secondary minerals for selected intervals of boreholes from site 1 is presented by Laurenzi el al. (2015).

After the borehole drilling was completed the instrumentation was installed in the borehole by attaching it to a central pipe (steel for the deep borehole and PVC for the shallow ones). A Geokon thermistor string and KE-50 Figaro oxygen probes were inserted in the borehole for monitoring of in-situ sulfide mineral oxidation.

Figure 2 Drilling sites. Arrows point to the monitoring borehole sites

To complete the installation, the borehole was backfilled with either silica sand/gravel, waste rock or bentonite using a tremie pipe. Each interval of the casing was retrieved one meter at a time during backfilling. Bentonite intervals were wetted with water to ensure proper sealing. The sensors were surrounded with material selected to optimize data collection, in the case of the oxygen readings, the probes were surrounded with quartz pea gravel.

Limitations

The construction of the boreholes was more difficult than initially anticipated. The height of the Antamina dump, the drilling method and the wide range in material size posed challenges for the successful completion of the installation. In particular, a deep borehole was considered to be included on site 1, but because of the difficulties this borehole was not completed at the time. The site 3 deep borehole has 2 sections of trapped casing underground (25 – 45 m and 100 – 120 m). These sections could not be brought back to the surface because the welds broke at the moment of casing retrieval.

RESULTS AND DISCUSSIONS

The sulfur content of the drilled material showed a high degree of heterogeneity with depth; the average sulfur content was 2.5%, but some of the intervals presented sulfur content up to 20%. The distribution of high sulfur content intervals is random, linked to the original lithology of the deposit. At Antamina, the abundance of carbonate rocks leads to acid-base-accounting (ABA) results that are mostly indicative of neutral drainage conditions, with a few exceptions in the high sulfur intervals.

The deep and shallow boreholes on site 3 (BH3d and BH3s respectively) show moderate oxygen depletion (i.e., about 10%-15% O_2) whereas the shallow borehole from site 1 (BH1s) shows steadily declining oxygen concentrations with depth to almost complete depletion at 20m depth (Figure **4**).

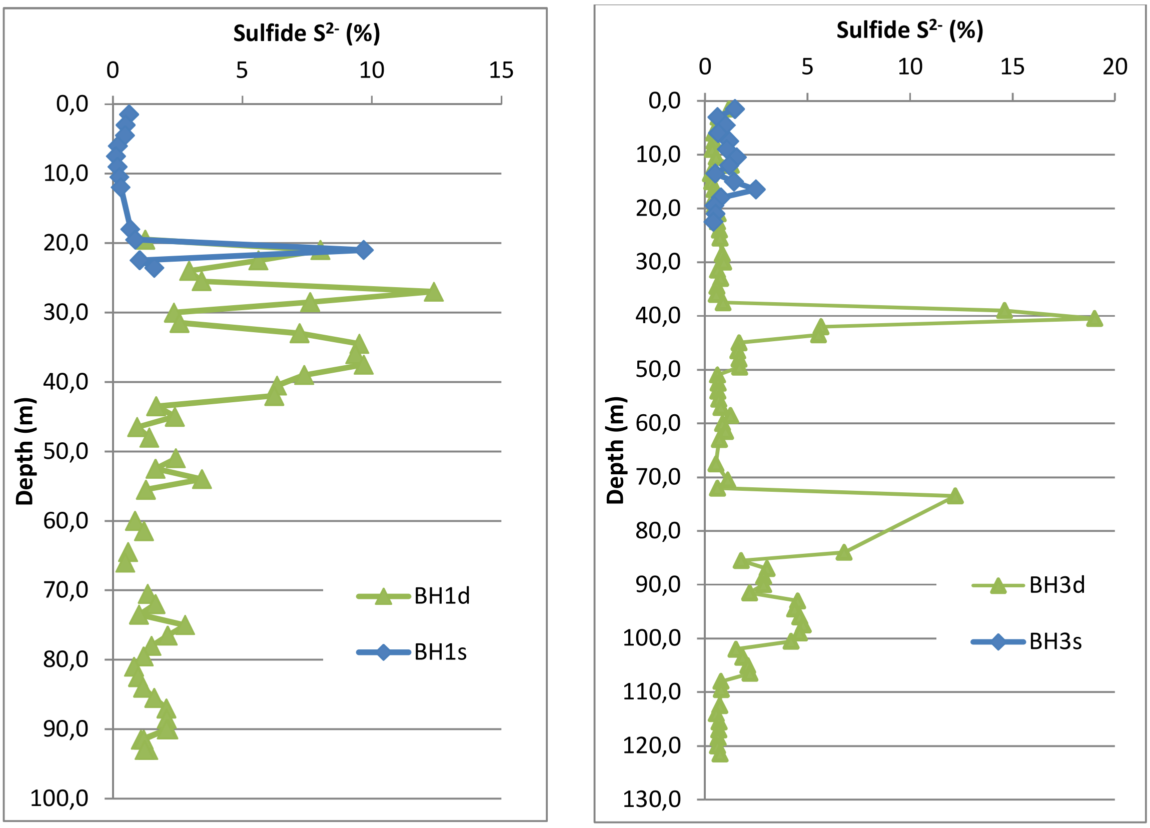

Figure 3 Sulfur content of the solid phase samples

Site 1 is warmer than Site 3, shows a higher degree of oxygen depletion and presents several intervals with higher than average sulfur content which could explain the increased reactivity. Nevertheless, higher overall sulfur content is observed in specific intervals at Site 3, .

The deep hole at Site 3 shows an increase in temperature at 40 m depth and then a decrease at 65 m. The same pattern is repeated at the bottom of the borehole. The lower temperature zones are correlated with the base of the lifts on which the dump was constructed. These zones are presumed to be a result of the lower reactivity of the boulders that rest at the base of each lift.

Waste rock dumps built by end dumping are segregated with coarse material resting the bottom, producing high permeability areas for oxygen ingress, similar to what Wels et al. describe as the “chimney effect”. In the case of the borehole BH3d it is observed that O_2 content is higher in the location where coarse fragments are located (60-70 m), but rapidly decreases again in the new lift, where it is expected that fine material is present, but also there is an increase in sulfur content at 75 m.b.g.s.

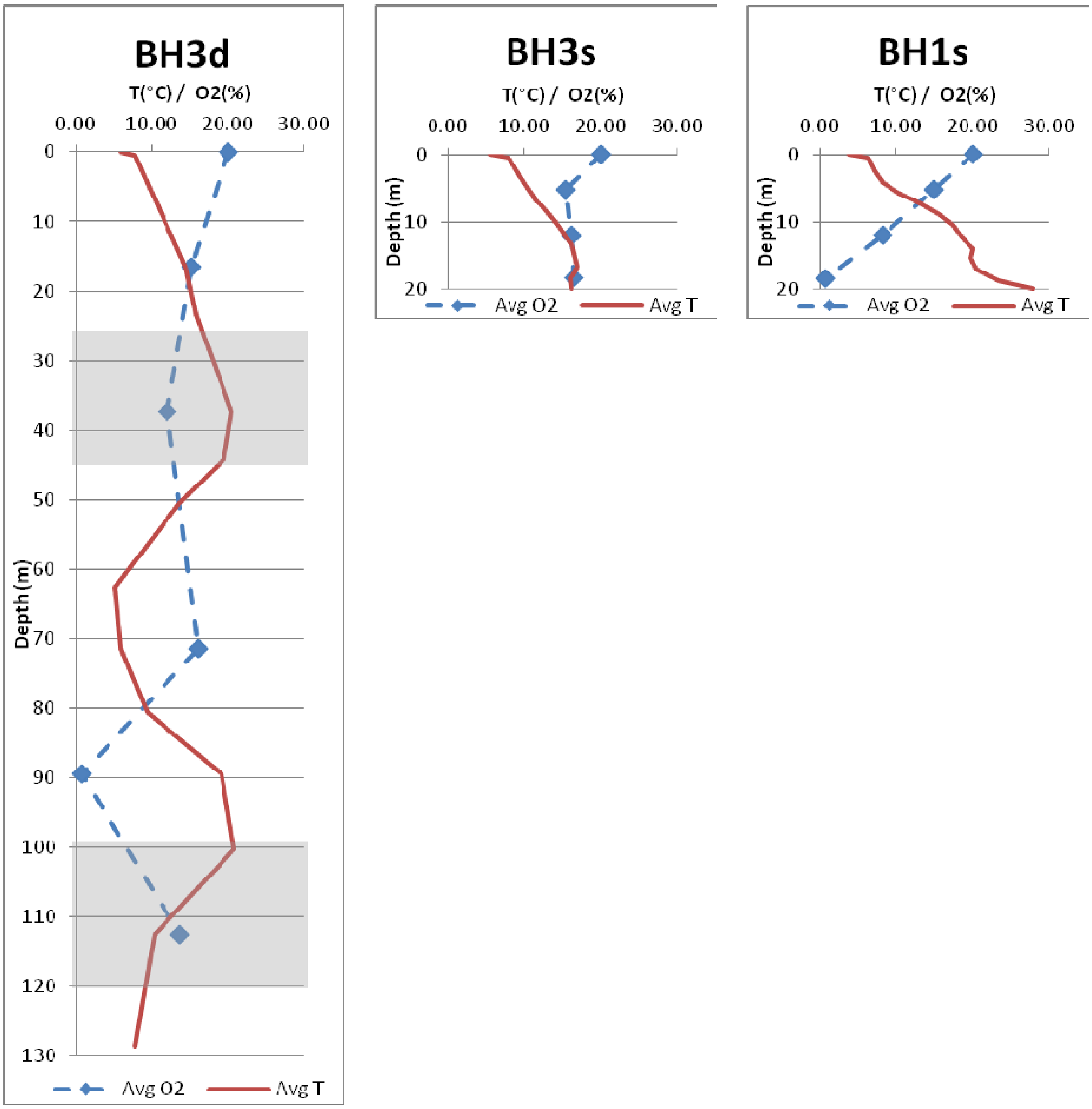

Figure 4 Average O_2 and T profiles for the boreholes. The shaded areas for BH3d represent the trapped casing

When oxygen is supplied by 1D-diffusion only, the oxygen concentration at depth can be solved analytically (Ritchie and Miskelly, 2000):

$$u(x) = \frac{\cosh(\varepsilon(x-1))}{\cosh \varepsilon} \quad (1)$$

$$\varepsilon = \sqrt{\frac{h^2 S_o}{D C_o}} \quad (2)$$

$$X_l = \sqrt{\frac{2 D C_o}{S_o}} \quad (3)$$

where u is the oxygen concentration as a function of $x = z/h$, z is the depth, h is the height of the pile, S_o is the intrinsic oxidation rate, D is the effective diffusion coefficient, C_o is the oxygen concentration at the surface and X_l is the diffusion length. The oxygen concentrations expected using these equations are shown in Figure 5.

The oxygen concentration profiles differ from an expected diffusion profile, and this could be explained because of either heterogeneity leading to complex diffusion patterns in three dimensions or gas migration processes other than diffusion, namely convection/advection. The isolated zones of high temperatures and low oxygen in the deep borehole (Site 3) indicates the presence of reactive hotspots and complex pore gas migration patterns that are not consistent with 1D-diffusion as explained by Ritchie and Miskelly (2000).

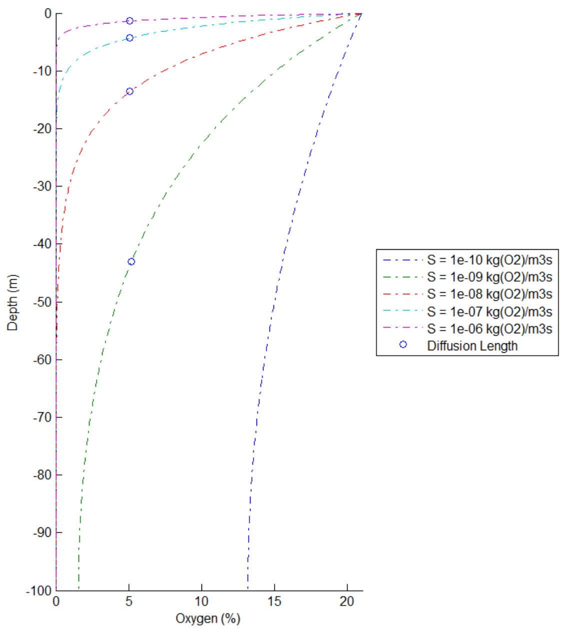

Figure 5 Expected oxygen concentration profiles for varying range of intrinsic oxidation (S) in a hypothetical 100 m tall dump considering homogeneous oxidation rate and 1D-diffusion as the only oxygen supplying mechanism

A previous study in an 10 m high experimental waste rock pile at Antamina showed decreased oxygen concentration down to 7% (Singurindy et al. 2012). The temperature increase at the experimental pile scale was up to 13.3 °C. It was observed at the experimental pile scale that the zones of greatest oxygen depletion were well correlated with the traffic surface, whereas at the operating dump scale zones in the interior of the dump show the highest degree of oxygen depletion. The experimental pile material is comprised of sulfur up to 4.6% which is lower than the high sulfur intervals of the dump.

Based on these results, the chemical and physical heterogeneity play important roles in the oxygen demand and distribution within waste rock dumps. Other factors, such as moisture content will affect fluid transport; increasing moisture content limits the ingress of fresh air into the dump by decreasing the air permeability and diffusivity.

CONCLUSIONS

We measured oxygen concentration and internal temperature within an operational waste rock dump. There is evidence of sulfide mineral oxidation at the two investigated locations. Areas of increased reactivity (elevated temperature and low pore gas oxygen) corresponded to intervals of waste rock with high sulfur content. Oxygen content and temperature were highly variable within the investigated dump, inconsistent with a 1D-diffusion – dominated system. The nature of temperature and oxygen profiles indicates the presence of reactive hotspots and complex pore gas and pore water migration patterns. It is often conceived that gas distribution in waste dumps is relatively smooth. This might be the case in relatively homogeneous dumps, however we show that in the presence of geochemical and physical heterogeneity this conventional view is not applicable. Because of the variability of waste rock, we recommend site-specific investigations.

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