



## Deep well rinsing of a copper oxide heap

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### ABSTRACT

A subsurface irrigation test, using a series of four rinse wells, was conducted on a copper oxide heap leach pad over a three week period. The pad has been significantly underperforming due to difficult drainage conditions imposed by a high degree of fine-grained material. The test was to determine whether it would be feasible to conduct the directed leaching method across the entire pad assuming that enough copper is liberated to pay for the upscaled well field installation. The rinse wells were connected directly to an existing raffinate line. Validation of the test included 1) hydraulic monitoring to ensure sufficient solution flow and coverage in the formation and 2) metallurgical monitoring of solution samples extracted from nearby monitoring wells to ensure copper liberation. The results showed that the mean flow rates to each rinse well exceeded expectations by a factor of at least 1.5 for an extended period of time, that radial solution coverage for optimal operating conditions was approximately 17 m, and copper grade was upwards of three times the anticipated grade. The test was then extended for an additional two months on a single well, where the copper grade remained approximately two times higher than that from surface irrigation. By the end of the testing, it was calculated that at least 191,000 kg of copper was liberated. The upscaled program is to include 170 additional wells spaced 31 m apart and the potential for 12 wells to be rinsed simultaneously, which would allow the program to be completed in less than three years.

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### 1. Introduction

It appears rather clear that processing of low grade metallic ore in a surface-irrigated heap leach facility is a mature technology (Schmuhl et al., 2011), owing to the many works dedicated to the topic (see Watling, 2013 and references therein) and the large number of mining facilities worldwide that have adopted it (Ghorbani et al., 2011). At a high level, applying solution to a large rock pile and collecting the liquor at the outlet would give the impression of a simple system. Heap leaching, however, is deceptively complex, and Dixon and Petersen (2003) distinguish a range of different processes occurring from the macroscale of the entire heap (e.g., solution flow, heat balance, gas advection) down to the mineral grain-scale (solid surface processes, reactive constituents, redox chemistry). Much of the early research in heap leaching went to conceptually understanding these processes and developing mathematical models to predict behavior (Roman et al., 1974; Shafer et al., 1979; Letowski, 1980; Bartlett, 1992; Dixon and Hendrix, 1993). With these efforts have come large-scale spatio-temporal phenomenological models that can track moisture, metal recovery and remaining inventory, temperature, air movement, and cyanide or free acid consumption (Cross et al., 2006; McBride et al., 2012).

More recently, a significant focus has been on improving or optimizing the heap leach process, with a mindful eye towards economic forces that include market prices, recovery time, and expenses, balanced with mining constraints as related to heap height, particle size, irrigation rate,

and other factors (Padilla et al., 2008). Operationally, Mellado et al. (2011) and Trujillo et al. (2014) examined optimal heap leach design criteria in maximizing a mine's metal recovery and hence income. Besides ore grade, other important factors included heap height, cycle time, and the number of simultaneously operating heaps as major factors to consider in designing a profitable facility. At a microscale and without considering economics, Petersen and Dixon (2007) optimized zinc recovery by adjusting heap height, irrigation rate, acid concentration, and solution temperature. Devenci et al. (2003) investigated optimum temperatures, pH, oxygen demand, and nutrient loads for bioleaching of sulfidic minerals. Other examples of optimized parameterization of leaching processes include those works by Bouffard and West-Sells (2009), Garcia et al. (2010), and Mellado et al. (2010).

Despite all of the best efforts to optimize engineering parameters at the onset of heap design and to make adjustments to the process through implementation, there is still a great potential for metal to be left behind. Using a simple example of a 0.25% acid soluble copper grade in a 50 million-ton stockpile, for every percentage of unrecovered metal there are 2.5 million pounds of copper internally distributed and potentially available for continued leaching. Extracting this last bit of material from the stockpile, however, can be challenging unless the nature of the solution delivery system is drastically changed. As many have discussed so far, preferential flow of leach solution (e.g., Orr and Vesselinov, 2002; Wu et al., 2007, 2009) will inhibit uniform wetting and drainage through all pore space. These flow channels cannot easily be broken unless the pore pressure is redistributed in favor of flow towards underleached areas (by substantially reducing the irrigation

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rate for an extended period of time) or through hydraulic alteration of the pore structure. The latter can be achieved through pressurized delivery of leach solution via injection wells (e.g., Seal et al., 2012), where the wash-out of fines has been hypothesized to increase the hydraulic conductivity and expose new surfaces to barren leachate (Winterton and Rucker, 2013).

While the hydraulics of this new pressurized solution delivery method has been investigated in some detail (Rucker et al., 2014), the potential for metal liberation has not. In Seal et al. (2011) the PLS grade in the reclaim pond was used to estimate additional gold recovery above a hypothetical baseline and it was suggested that upwards of 4500 troy ounces was recovered as a result of the injections. Unfortunately, there were many parts of the heap leach pad reporting solution arrival at the reclaim pond, thus providing a level of unquantifiable uncertainty associated with that recovery estimate. In this work, a great deal of effort was expended to quantify the real liberation at the point of delivery using both rinse and solution monitoring wells. A distinction is made here between injection wells used in previous works and rinse wells, where rinse wells are connected to existing irrigation piping without the use of external booster pumps and apparatus to segregate individual zones along the well. The demonstration of rinse wells is conducted on a copper oxide run-of-mine stockpile and the solution coverage, metallurgical parameters, and hydraulic alteration are quantified to allow for upscaling the operation pad wide.

## 2. Ore description

Copper extraction from the leach pad has consistently fallen short of forecasts due to the difficult drainage conditions imposed by fine grained material. It is estimated that copper recovery is near 40% for the 40 million ton heap with average acid soluble copper grades of 0.25%. After an extensive drilling campaign to characterize the pad, it was discovered that fines, as defined by those particle sizes passing the 200 mesh (0.075 mm), ranged from 5 to 26%, were evenly distributed throughout the depth profile but were stratified within individual lifts, and the assayed parameters of particle size distribution and total residual copper exhibited high spatial variability. These observations lead back to the specific type of ore and host deposit, which is a dual-centered landslide breccia deposit comprising mainly of schist with supergene mineralization sometime from the Eocene to late Miocene. The deposit is covered by dacite and a relatively well cemented tuff, where mineralization has also occurred. A major fault lies between the two breccia-host mineral centers and is itself hosted in brecciated diabase.

Chrysocolla generally fills the clay-rich matrix of the brecciated deposit, the fault, and open fractures within the schist and diabase immediately in the footwall zone of the fault, dacite, and larger clasts of the breccia. Malachite is locally abundant in the deposit and sporadically along the fault. Chalcocite is the only significant copper sulfide mineral present and is restricted to the lower parts of the deposit. Chalcocite is commonly found rimming or partially to totally replacing pyrite, which is often found as veinlets or individual grains within breccia clasts.

Acid consumption is the highest for material within the fault zones, and particularly from the low lying fault which establishes the bottom of the pit area. Here, precipitation of elements such as calcium, magnesium, zinc, aluminum, etc. during the formative events of copper mineralization, give rise to sulfuric consumption on the order of 50 kg/tonne according to 24-hour bottle roll tests. This value is steady over the depth of extracted samples, except for the bottom of each drill hole tested (representing the bottom bench of the pit).

After blasting, the ore is trucked to the heap for placement and surface leaching. Surface leaching occurs at an approximate rate of 6 L/h/m<sup>2</sup>. Early in the heap's development, the trucks dumped their load to be spread by dozer, and there was significant traffic on the heap. Lift heights were upwards of 10 m. Approximately three years ago, small conveyance stackers were introduced to reduce the compactive forces from haul trucks and lifts were reduced to 5 m. Interlift drains have also been placed along a few lifts to help move the pregnant leach solution out of the heap more expeditiously and to reduce build-up of hydraulic head at the interface between the truck dump and conveyance stacker portions of the heap.

## 3. Methodology

Given the low recovery, a secondary recovery method using subsurface irrigation was chosen. This type of solution delivery can be applied in a number of ways that include adjusting variables associated with application pressure, number of injection zones per well, consideration of extraction wells, drilling method, well casing, and well screening materials. For the injection examples presented for gold mines (Seal et al., 2011, 2012; Winterton and Rucker, 2013), the drilling method was dual rotary that advanced the steel casing during drilling to ensure tight contact between with the formation, which minimizes the potential for blowout of the well. The wells were perforated in-situ at multiple zones and a high pressure booster pump was employed to maximize the solution coverage for each zone. The high pressure allowed for well

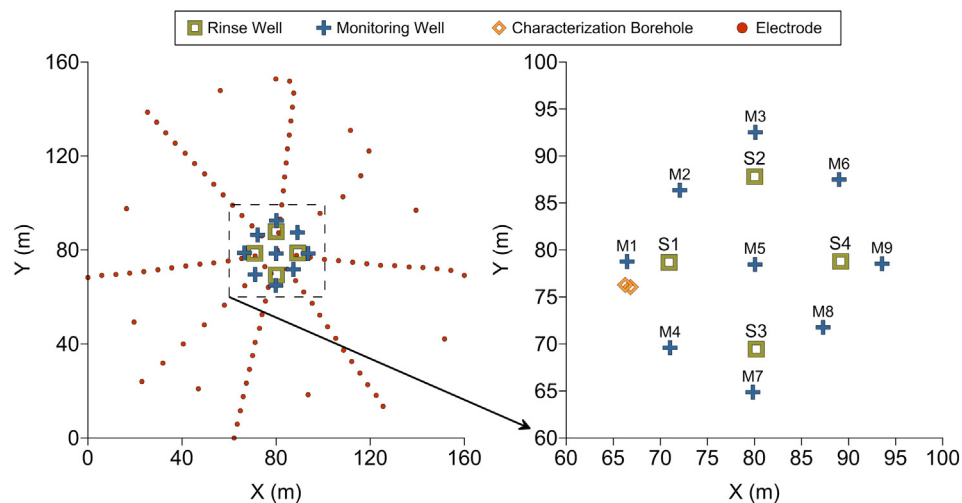


Fig. 1. Layout of the rinse and monitoring wells for secondary recovery of copper. Positions of stainless steel electrodes are also shown, which were used to image the solution propagation using electrical resistivity geophysics.

**Table 1**  
Operating hydraulic parameters during the rinse tests on individual and combined wells.

Test	Duration (days)	Max flow (L/h)	Mean flow (L/h)	Total flow (m <sup>3</sup> )	Avg. tophole pressure (bar)	Est. bottomhole head (m)
S1	5	180,000	135,000	5150	0.3	24
S2	4	210,000	146,000	4830	1.15	39
S3	5	191,000	132,000	4550	0.23	27
S4	3	208,000	159,000	4090	0.83	39
Combined	1.2	340,200	336,800	9820	−0.43	22

placement as far as 35 m from each other using flow rates in excess of 180,000 L/h and pressures near 20 bar.

In the present application, a hollow stem auger was used for drilling the rinse wells, using PVC casing that was lowered into the hole, and backfill comprising fine-grained material. Since no high pressure booster pump was to be used for the experiment, it was thought that the well design would accommodate the lower pressures with no blowout. Additionally, the open hole allowed for monitoring sensors to be placed deeply within the heap along the well annulus. The wells had a single application zone at the bottom of the well. At the top of each casing was a valve and a port for monitoring pressure. All wells were plumbed back to an existing irrigation line which had an inline flow meter and totalizer that recorded solution delivery solely to the rinse wells. The monitoring wells were installed in the same manner, but were placed deeper than the rinse wells.

Fig. 1 shows the layout of the four rinse and nine monitoring wells. The rinse wells were screened over a 3 m interval, with each well having a different final screened depth between 21 m and 30 m below pad surface. The monitoring wells were screened from 37 m to 46 m. Rinsing was initiated on S1 and continued clockwise around the individual wells. Solution was applied between three to five days per well and only during daytime operating hours. A second test was conducted, where all four rinse wells received solution for a continuous 30 h. Lastly,

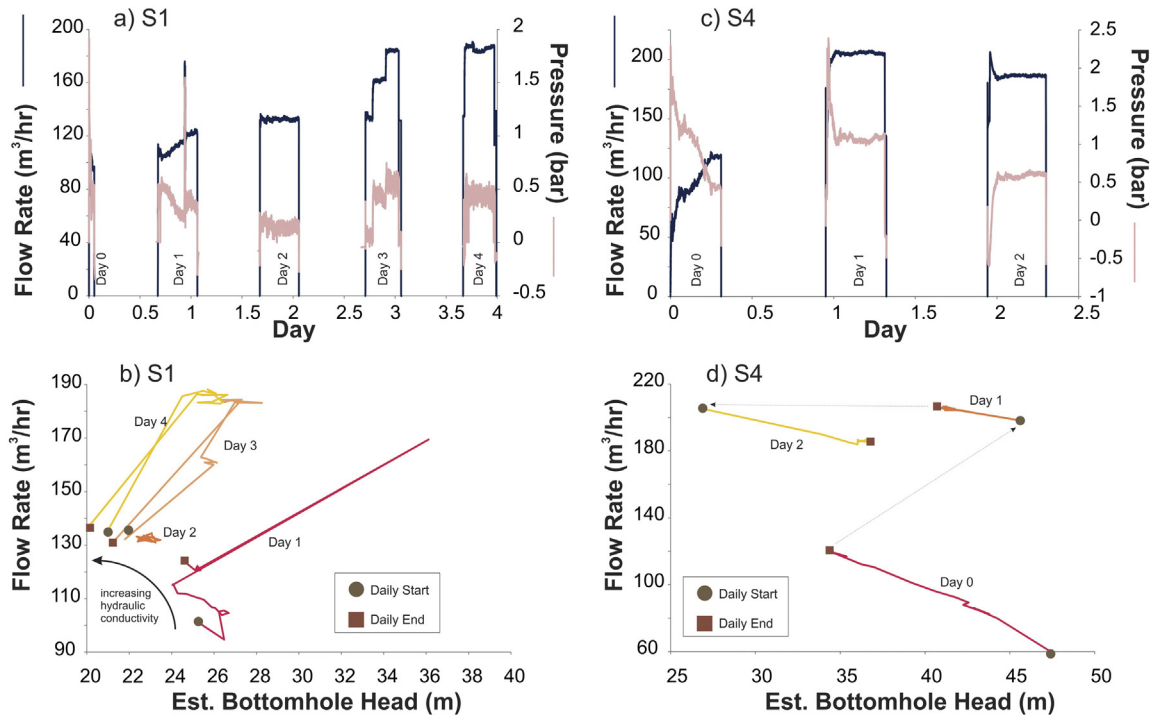
a final test included rinsing on well S1 for an extended period of time to watch the drawdown of resources and determine upper limits for total recovery during a pad wide implementation of the technology.

## 4. Results

Operating objectives were initially developed for the rinsing test that included a minimum flow of 90,000 L/h with a net copper grade of at least 0.8 g/L averaged over a single eight hour period. The objectives were developed as a means for recuperating costs associated with drilling, assuming \$6000 US\$/ton of Cu. In order to verify that these objectives were met, a number of different monitoring strategies were employed that measured aspects of solution flow and coverage and concentration of key cations and other geochemical data.

### 4.1. Hydraulic monitoring

Hydraulic monitoring of the rinse test included measuring flow and pressure parameters in-situ. Both the flow meter and pressure gage recorded data every 10 s to allow for a highly resolved temporal understanding of solution availability and material breakdown within the heap. Table 1 lists the final hydraulic operating parameters for the different tests, which shows that the flow rate objective was exceeded by at least a factor of two. As a matter of perspective, a mean flow rate of 140,000 L/h would be equivalent to 23,333 m<sup>2</sup> of surface leached area (assuming 6 L/h/m<sup>2</sup>). In addition, the mean pressure is shown to be extremely low. Fig. 2a shows the time history details of flow and tophole pressure during rinsing of S1 and explains the low pressures observed for the tests. During the first three rinse days (Days 0, 1, and 2) the flow was throttled back to ensure that blowout was not going to occur. The exception was on Day 1, where a brief full-throttle test was conducted; blowout did occur and solution leaked up the well annulus. Low flow continued through Day 2, where pressures are shown to decrease and become negative as soon as the well is shut in for the



**Fig. 2.** Flow and pressure (or head) data for rinse wells S1 and S4. A) time history of flow rate and tophole pressure for S1. Up through Day 2, flow rates were throttled back to allow a maximum rate of about 130,000 L/h, after which the valve was open to allow full flow. B) Flow rate versus bottomhole pressure head for S1 showing permanent hydraulic changes in the formation through washout of fines. C) Time history of flow rate and tophole pressure for S4 with full flow of raffinate at the beginning of the rinse test. D) Flow rate versus bottomhole pressure head for S4 showing washout and void creation for Days 0 and 1 and void filling for Day 2. Note — Bottomhole head was estimated from the column of solution in the rinse well added to the tophole pressure and assuming no pipe friction or head loss through the screen.

day. On Day 3, flow was again increased, but gradually to help stabilize the formation. At each jump in flow, the pressure correspondingly increases.

Fig. 2B directly compares the change in flow to the change in head, as estimated at the bottom of the well (assuming zero pipe friction and head loss). The ratio of the two values is a measure of the hydraulic conductivity (Winterton and Rucker, 2013). In the broad view, the hydraulic analysis shows an initial low flow/high head scenario. By the end of rinsing on Day 4, head is low with a much higher flow rate. The changes are observed to be progressive and permanent as the flow rate does not return to the same lower value from the start of each day. Winterton and Rucker (2013) described this phenomenon as washout of fines, leaving coarser grained material near the injection zone. Pressures are reducing throughout the test due to less energy needed to move a unit volume of raffinate through the larger pores devoid of fine-grained material. Moving from lower right to upper left on this figure corresponds to an increase in hydraulic conductivity. When the well is shut in each day, the solution immediately drains with the large pore spaces emptying first and creating a vacuum at the well.

Fig. 2C and D represent the same series of plots for well S4. Whereas S1 was screened the shallowest at 21 m, S4 was the deepest at 30 m, and the decision was made to allow full flow to start at the beginning of the rinse period. For the first day (Day 0), the pressure drops precipitously as the flow correspondingly increases, and there appears to be significant washout of the zone. The initiation of flow on Day 1 starts out at values almost double of that for the previous day and ends with slightly lower heads and higher flows relative to the beginning of the day. On

day 2, the paradigm shifts and the hydraulics move from high flow with low head to low flow and high head. The shift in hydraulic performance is likely due to void filling from finer grained material above the screened interval. At the extreme end, the high pressure and flow rate could have created a small cavity and sometime between the end of Day 1 and the beginning of Day 2, the material above collapsed into the cavity causing the hydraulic performance that appears to be opposite of all other rinse cycles.

#### 4.2. Geophysical monitoring

The second level of in-situ monitoring included the use of time lapse electrical resistivity to observe the volumetric changes associated with fluid saturation, porosity, and ionic constituents of the raffinate. General information about the time lapse electrical resistivity method applied to subsurface injections can be found in Rucker et al. (2009, 2014) and Rucker (2014). For monitoring the rinsing tests, 168 electrodes were distributed along the surface and within the annulus of each well to provide a highly detailed spatio-temporal rendering of the solution propagation. Fig. 1 shows the positions of the surface electrodes, where each electrode comprised of 1 cm diameter stainless steel rod, approximately 20 cm long. All of the electrodes were wired back to a central acquisition unit, capable of completing a set of measurements (or snapshot) within 25 min. Each measurement in a snapshot comprises 167 voltage values while transmitting electrical current on the 168th electrode using a pole-pole array; each electrode has a turn at transmitting current to complete the measurement set. A single snapshots will contain 28056

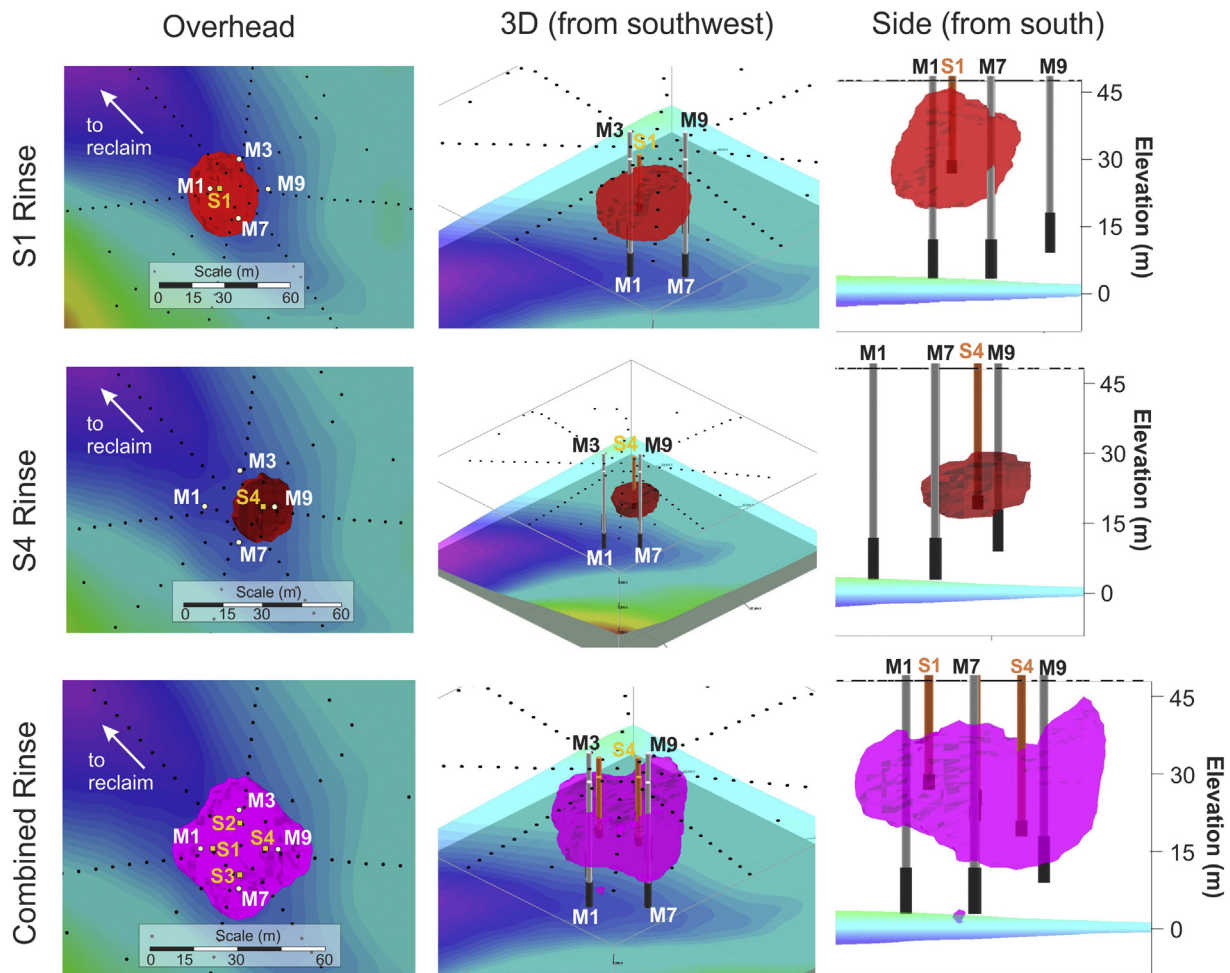


Fig. 3. Electrical resistivity results for three rinse tests showing 5% change in resistivity compared to a baseline value prior to each rinse test. The rendered three-dimensional bodies are a best estimate of solution propagation from the rinse well.

data values and each day of monitoring will produce approximately 57 snapshots.

Fig. 3 shows the results of the electrical resistivity survey. The figure presents the outcome from three rinse tests, including S1, S4, and the combined rinsing on all four wells simultaneously. The figure also presents three different views of each test. For reference, rinse wells and several monitoring wells are placed at the appropriate position and depth. Screens for each well are also shown as larger diameter portions of the well bottom. Lastly, the underliner is shown as color contoured plane with the route the solution would take to the reclaim pond. Directly beneath the well field, the liner was approximately 50 m.

The rendered three-dimensional bodies for each rinse test was developed by calculating a percent difference for the final snapshot, just prior to well shut-in, to the baseline prior to the test start. A representative percent difference value was chosen, equal to 5% for each test. Smaller values of percent change would have produced a larger body. The 5% percent change was ultimately chosen based on secondary information regarding the benchmarking of solution location from the change in electrical current output from the boreholes electrodes, as described in Rucker et al. (2014). Also, it is important to note that the last few hours of monitoring for each rinse test produced the same sized body, suggesting that the solution reached a steady state lateral flow. The results show that the S1 rinse test pushed solution out to approximately 17 m from the well to cover an area of approximately 907 m<sup>2</sup>, S4 rinse test pushed solution to 12 m, and the combined rinse pushed solution to 24 m (as measured from the center of the well field).

Again, as a simple matter of perspective, the solution coverage for an equivalent surface leach with 140,000 L/h is 23,333 m<sup>2</sup> (or 86 m radius). Curiously, the solution from the S4 rinse test did not reach as far as S1, despite having higher mean and maximum flow rates. This is likely due to the fact that full throttle was initiated immediately on this well, washing out larger grained material than that of S1. The result would have been a larger pore volume capable of limiting the flow outward from the well. This was confirmed by observing extremely turbid solution from well samples taken from M9.

#### 4.3. Metallurgical monitoring

During the course of the rinsing, samples were drawn from the bottom of each monitoring well, two interlift drains located at the edge of the pad (approximately 80 m away), and the raffinate. The sampling rate was higher for those monitoring wells closer to their respective rinse wells, with other wells farther afield sampled less frequently. The sampling procedure included evacuating the well with at least one well volume plus the volume in the hose pump before collecting 1 L of solution for testing. In many cases, several well volumes were purged before testing. The solution sample was split, where half stayed locally onsite for testing pH, electrical conductivity, and oxidation–reduction potential (ORP) and the other half going to an analytical lab for a detailed analysis of free acid, copper, iron, and other cations.

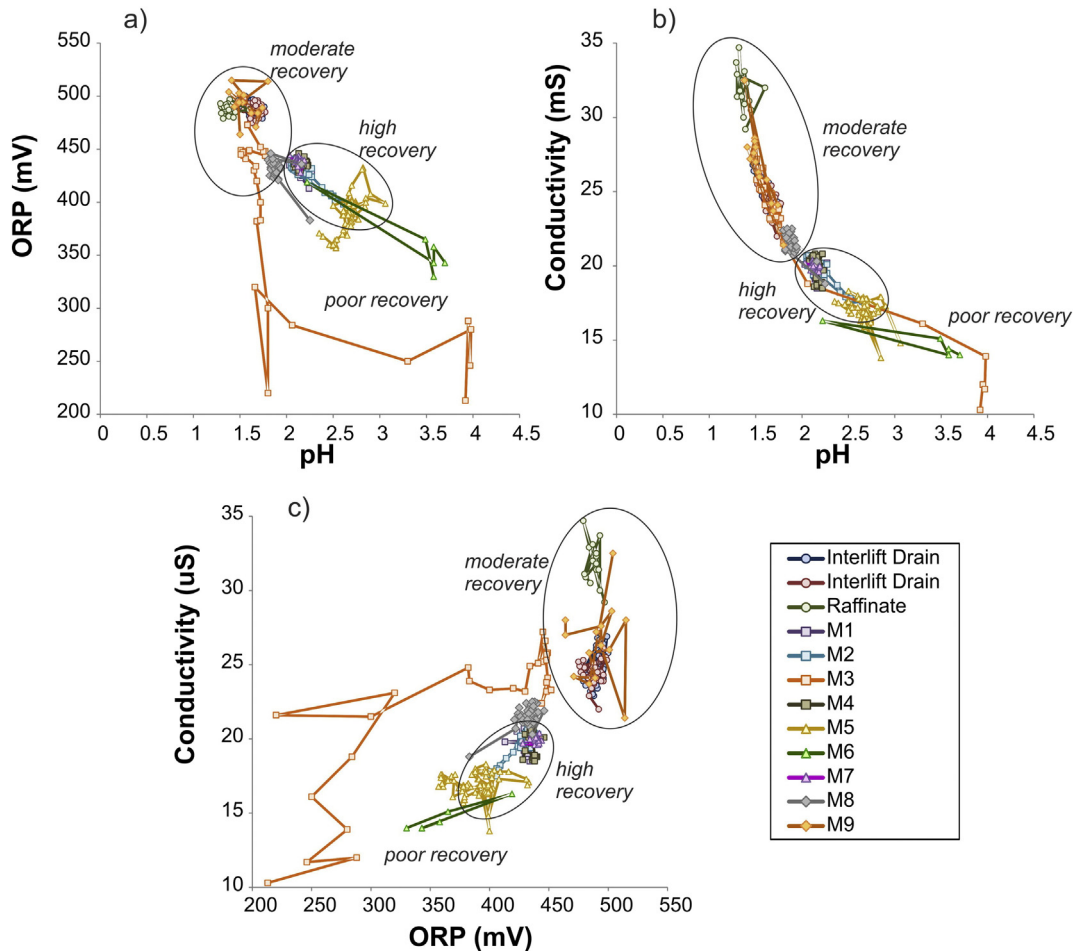


Fig. 4. Simple metallurgical parameters acquired from nine monitoring wells, two interlift drains, and raffinate. A) ORP versus pH. B) Conductivity versus pH. C) Conductivity versus ORP. Qualitative information is also provided on the scatter plots to indicate poor, moderate, and high copper recovery based on copper grades obtained from the same samples: Poor recovery are those copper grades that are less than measured in the reclaim pond; moderate recovery are copper grades equivalent to the reclaim pond (excluding raffinate); high recovery represents copper grades greater than the reclaim pond. Fig. 5 shows the time series of copper grades.

Fig. 4 shows the results of the simple metallurgical parameters measured onsite, presented as a scatter of one parameter versus another. The data are segregated among the different monitoring locations and show clear groupings associated with each location. As will be discussed below, some wells exhibited high copper recovery whereas others had poor recovery. Moderate recovery (excluding the raffinate) represented those wells and drains that resembled the copper values in the reclaim pond. The monitoring wells with measured high copper recovery generally coincided with rinse wells S1 and S3, which were screened the shallowest at 21 and 24 m, respectively. Assaying of cores before rinsing began showed that the remaining copper was indeed at these shallower depths. Additionally, poor recovery from monitoring well M6 was due to the fact that it was likely not constructed well and very few samples could be taken from it.

Time series data showing copper, free acid, and pH are presented in Fig. 5. Vertical gray bars distinguish each rinsing period. The qualitative recovery determination from Fig. 4 was taken from the copper data of Fig. 5. Monitoring wells M1, M2, M4, M5 and M7 consistently show copper above 2 g/L. During rinsing on S2, well M2 briefly nears 4 g/L copper, which also corresponded to a decrease in free acid and increase in pH. Monitoring well M8 dropped over time to about 1.5 g/L. Moderate recovery, where values were near 1 g/L, included the interlift drains and M9.

One sign that new leaching is occurring as opposed to simple flushing of previously liberated copper can be observed in the free acid data. Free acid of the interlift drains, which drains solution from surface irrigation, is near 3.5 g/L. Monitoring wells that showed high recovery measured free acid near 1 g/L. Well M3, which is nearest rinse well S2,

**Table 2**

Average elemental grades from gangue minerals during the rinse test.

Element	Well M2	Well M5	Drain 3900B	Drain 3915B	Raffinate	Effect from rinse vs surface leach
Zn (g/L)	0.020	0.019	0.015	0.015	0.015	Higher
Mn (g/L)	0.18	0.18	0.15	0.15	0.15	Higher
Mg (g/L)	2.16	1.93	1.97	1.99	1.92	Higher
Ca (g/L)	0.15	0.21	0.16	0.19	0.15	Higher
Na (g/L)	0.19	0.18	0.19	0.19	0.18	Same
K (g/L)	0.17	0.18	0.17	0.17	0.17	Same
Al (g/L)	1.99	1.88	2.05	2.09	2.04	Lower

showed very low acid until full throttle flow started on S2, after which free acid increased significantly. It is likely that the fine grained particles that were washed away from the rinse well had significant copper associated with them.

Another view of enhanced leaching associated with the rinse wells compared to surface leaching can be gained by looking at the gangue chemistry. Table 2 lists the average grades throughout the test for many elements that are associated with gangue mineralogy, including zinc, magnesium, calcium, and others. To reduce complexity of the data, only two wells are presented to represent the effects from rinsing. These data are compared to the grades from the two interlift drains, representing surface leaching, and to the input raffinate. The last column of Table 2 qualifies the effect from rinsing by comparing the ability to leach specific elements relative to those data measured from the drains. Zinc, manganese, magnesium, and calcium show a greater ability to be leached from rinsing relative to surface leaching. Monitoring well

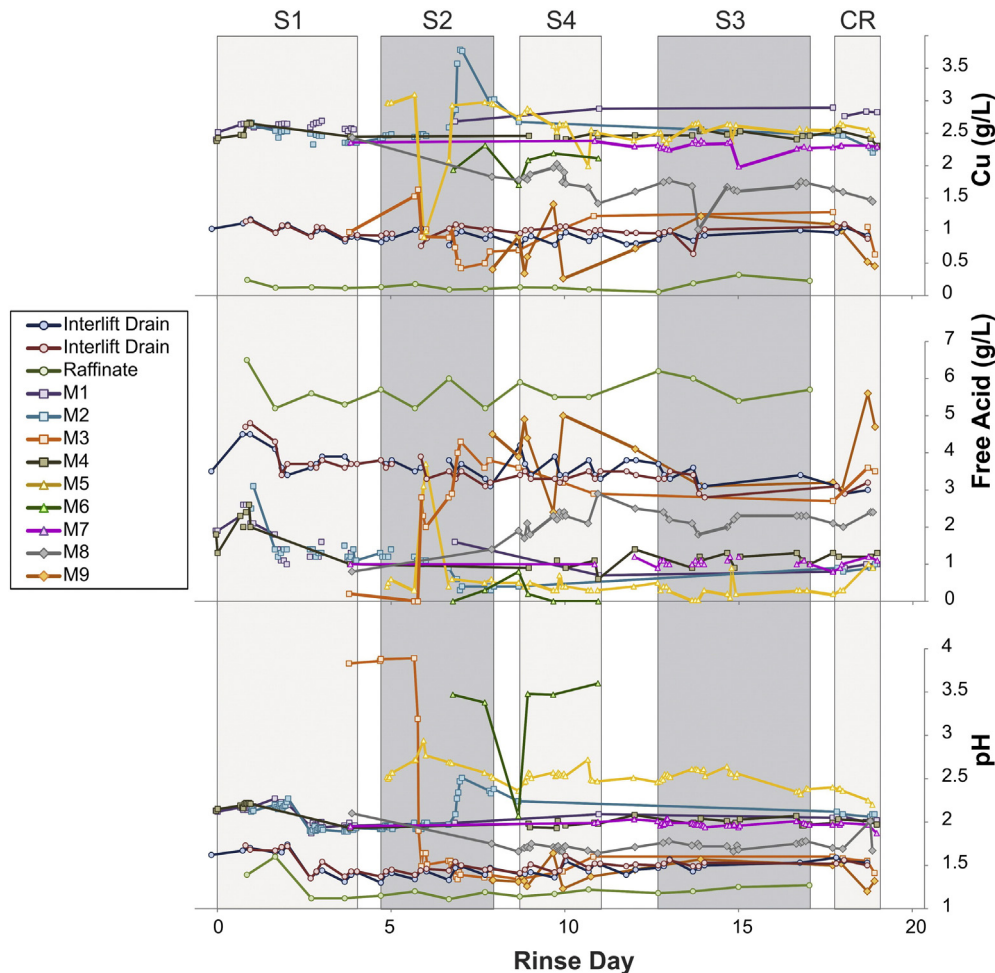


Fig. 5. Time series of analytical solution chemistry data from different monitoring locations during the five rinsing phases, including copper, free acid, and pH. CR = combined rinse.

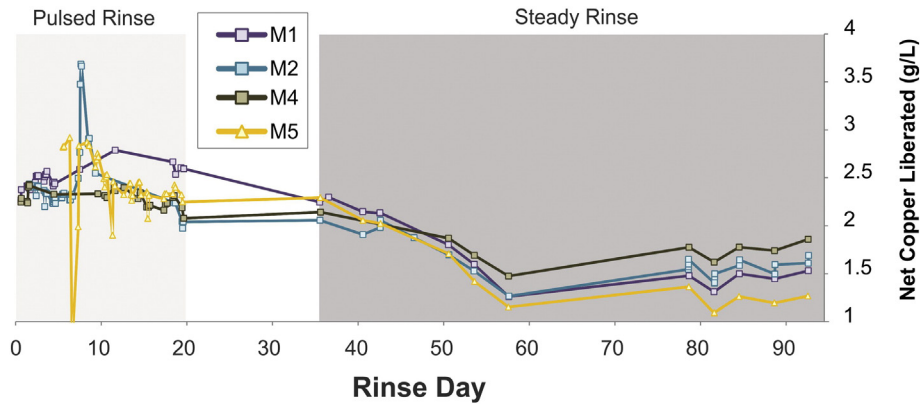


Fig. 6. Long term net copper liberated (total copper grade in solution – copper grade in raffinate) from four monitoring wells surrounding rinse well S1.

M2 shows a significantly higher average magnesium compared to the other sources and well M5 shows a significantly higher calcium. For sodium and potassium, the leaching from rinsing and surface leaching are roughly equivalent. The rinsing solution shows a much lower aluminum compared to surface leaching. One possible explanation for these observations is that the rinsing is more effective at breaking down the host diabase which is richer in magnesium and calcium, and less effective at leaching the schist. The diabase could be consuming more acid in its breakdown, which explains the time series data in Fig. 5.

As a last test, a steady rinse period of approximately 60 days was continued on S1 after a 15 day evaluation period following the pulsed rinse tests. The average flow over the steady rinse period was 90,000 L/h. Fig. 6 shows the net results of copper grade for the four monitoring wells surrounding S1. The net copper was calculated by subtracting raffinate copper grade from the total measured copper grade. The results show a sharp drop over the first 20 days once rinsing was reinitiated followed by a slight increase in grade for the test duration. During the time of sharp net copper decrease, copper grade increased in the raffinate due to issues in the plant, while total copper grade decreased only slightly (by 0.2 g/L). Total copper then remained relatively steady until the end of the test. Integrating the average net copper grade and multiplying by total solution delivery of 151,200 m<sup>3</sup> yielded approximately 191,000 kg of copper liberated during both the pulsed and steady rinse portion around S1. This value is approximately two-thirds of the

copper in a cylinder of 17 m radius and 50 m height assuming an average ore density of 1650 kg/m<sup>3</sup> and 0.45% stacked copper grade.

4.4. Direct characterization

As a final means of determining the effects of deep well rinsing on the heap leach pad, a drilling and assaying campaign was conducted, whereby a location near a rinse well was drilled immediately before rinsing initiated and approximately four months after rinsing ceased. Fig. 1 shows the locations of the pre and post rinsing characterization boreholes, which were 2 m apart and 5 m from S1. Grains size, moisture content, bulk density, and the metal content (copper and iron) were measured on 1.5 m intervals. Fig. 7a and b shows the changes in the physical aspect of the ore that include moisture and dry bulk density. The figure also includes the depth of the screened interval for the S1 well as reference. Both physical properties increase slightly after rinsing. The moisture content is expected to increase below the rinse zone due to the addition of raffinate, but the data shows the increase to be persistent along the entire length of the borehole. Fig. 3 explains the observed increase, where the geophysical imaging shows the affected volume from the rinsing to include areas that are near the surface. The bulk density also increases throughout most of the column, except the top 10 m. Anecdotaly, the surface elevation was monitored weekly during the pulsed rinse portion of the experiment, and a maximum 10 cm of

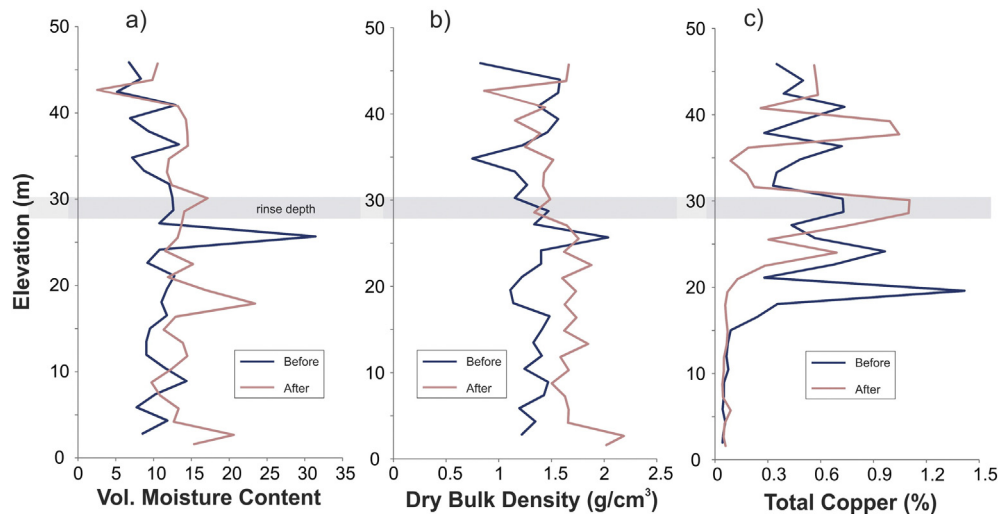


Fig. 7. Assay and grain size analysis from drilling near S1 rinse well. A) Volumetric moisture content, before and after rinsing, as a function of elevation within the heap. B) Dry bulk density as a function of depth. C) Total copper as a function of depth.

subsidence was observed in the center of the well field. The subsidence confirms the bulk density increase and could be due to a change in grain size density and the movement of fines or from cementation of pores.

Fig. 7c shows the change in copper near the rinse well. For the most part, and especially below the rinse zone, copper decreased substantially. The 5 m interval from elevations of 15 to 20 m, the copper reduced from a high value to equivalent residual values seen in lower parts of the heap (less than 0.1%). At the rinse depth and above, the copper values oscillate between more and less copper after rinsing. The increase in copper typically occurs where dry bulk density decreased slightly after rinsing and could be the result of a redistribution of smaller particles from washout. Regardless, there still remains significant mass of copper in this area and helps explain the sustained grade during the three month experiment.

## 5. Conclusion

A pilot-scale subsurface irrigation test to enhance the recovery of copper was demonstrated on a copper oxide heap. The test was designed with four rinse wells, with each well outfitted with a 3 m screen at depths that ranged from 21 to 30 m below pad surface. The rinse wells received solution directly from an irrigation line without the use of onsite booster pumping skids that have been described in other works (e.g., Seal et al., 2012). Flows to the well ranged from about 130,000 to 330,000 L/h.

A large effort was expended to validate the effectiveness of the method and ensure that initial test objectives were met. The test objectives were designed to offset drilling costs and included a minimum flow of 90,000 L/h and a time weighted average of 0.8 g/L copper in the pregnant solution sustained for at least eight hours. The validation measure included a number of monitoring technologies that measured in-situ hydraulic properties and ex-situ water chemistry data. Hydraulic properties were measured with flow and pressure gages and the data were recorded at a high sampling rate. Time lapse electrical resistivity geophysics was also used to track the movement of the pregnant solution. To obtain solution samples, monitoring wells were installed near the rinse wells and samples were withdrawn at sampling rates between one and 1 h.

By all measures, the pilot enhanced recovery test was a success. Maximum flow rates were at least double the objective and the mean flow rate was about 1.5 times the objective. The high flow rate also provided a means to washout the fine grained material near the wellbore and expose new surfaces to the raffinate. Wu (2006) discussed fluidization of particles during pressurized flow, whereby the drag forces of swiftly moving solution through the granular media causes the particulate material to unload due to tensile volumetric strain. Once this strain reaches a critical value, corresponding to the loss of contact between the particles in all directions, washout occurs. In extreme cases, the fluidization of all particles will cause cavity creation. Washout is an irreversible process, causing lasting changes to the pore structure, which was further demonstrated by plotting the time history of flow rate versus pressure head. By the end of each rinse test, the energy to move a unit volume of raffinate was much lower than the beginning of the test signifying an increase to the hydraulic conductivity.

Electrical resistivity geophysics was conducted to observe volumetric changes to the formation during rinsing. The resistivity parameter is sensitive to a number of phenomena occurring simultaneously, including saturation, porosity, and solution conductivity. The time lapse models showed a low resistivity body increasing outward from the well screen. When the well was shut in at the end of the day, the size of the body shrank until rinsing resumed the following day. The final position of the body at the end of each individual rinse test was used to infer the lateral solution coverage. Solution coverage was shown to be the largest in S1 and S2 (radial distance of approximately 17 m from the well center) when flow rates were gradually increased over a few days. This likely allowed only the smallest particles to move out of the fluidized zone first. As the drag forces increased due to increased flow towards the end

of the rinse, larger fine-grained materials became fluidized as well, producing a graded distribution of larger to smaller particles outside of the washout zone. In contrast, the rinse on S4 allowed high flow rates from the beginning, with a radial coverage of about 12 m. The high flow rates likely carried all fine grained material at once to an outer shell, which may have sealed off the formation and limited solution coverage. These ideas, however, need to be further validated.

Monitoring the metallurgical data from solution samples near the rinse wells showed that the potential for recovery of copper from underleached ore is significant. The copper grades exceeded the copper grade test objective by a factor of three in many cases and upwards to a factor of five for a short period in a single monitoring well. Additionally, the high grades were sustained for an extended period of time. Actual leaching was confirmed by the lowered free acid, which was significantly lower than those samples that represented surface irrigation. In fact, it appears that the acid consumption is about three times greater during rinsing than surface irrigation, which could be attributed to the greater surface area exposed during the hydraulic alteration of the pore space and fluidization of small particles and possibly from breakdown of diabase. If this is the case, then the hydraulics and kinetics are inextricably linked, which has implications for future detailed phenomenological models that wish to incorporate more heterogeneity in model parameters to understand localized processes. That is, it will be necessary to obtain site specific hydraulic data associated with the particle size distribution, which was shown to vary widely in this heap.

Using upscaled design parameters from the analysis of S1, the entire heap leach pad could accommodate approximately 170 wells spaced 31 m apart. The well design and well count assumes a setback of approximately 60 m from any edge and that the rinse wells would not be installed in areas where the liner is within 17 m from the surface. The wells could be grouped in pods of four to conduct a combined rinse in order to decrease time to completion. If each pod is to be rinsed continuously for three months, then it is estimated that the entire pad could be finished in about 8.5 years. Operating three well pods simultaneously reduces the time to less than three years. Additional recommendations for upscaling are to increase the free acid in the raffinate from about 6.5 g/L to 8.5 g/L (based on the near depletion of acid for a few monitoring wells as indicated in Fig. 5), have a single monitoring well per pod to continuously capture pH and conductivity of the pregnant solution to determine if optimum recovery is occurring, and a robust side slope monitoring program to ensure geomechanical stability of the heap.

Lastly, the economics of this operation can be shown to be highly profitable, even at low grades, if conducted at the end of the mine's life prior to closure. At this point, a minimal crew and equipment are needed to continue the rinsing and the costs per pound of copper to produce reduces by almost \$1 USD compared to full mine operation with blasting, hauling, and stacking, in conjunction with surface irrigation.

## Appendix A. Copper liberation during injection

Copper liberation from the injection test was calculated from the S1 injection well by integrating the time series of copper grade from wells M1, M2, M4, and M5. The grade from each well was integrated separately and an average grade was calculated by dividing by the time period over which the test was performed. The same procedure was performed for the raffinate grade, which was subsequently subtracted from the total grade to produce a net grade. Table A.1 lists the integrated values from the test.

**Table A.1**

Averaged total copper grades from solutions extracted from the monitoring wells during injection (in g/L). Net grade can be obtained by subtracting the raffinate copper grade by that measured in each well.

Injection period	M1	M2	M4	M5	Raffinate
Pulsed	2.65	2.58	2.48	2.55	0.14
Steady	2.09	2.00	2.15	1.86	0.34

The average net copper grade (in mass per volume) from each well was then multiplied by the volume of injected raffinate to calculate the mass of copper liberated during the test as follows:

$$\text{Copper liberated} = [(2.65 + 2.58 + 2.48 + 2.55)/4 - 0.14] \text{ (g/L)} * 5,140,800 \text{ L} + [(2.09 + 2.00 + 2.15 + 1.86)/4 - 0.34] \text{ (g/L)} * 105,840,000 \text{ L}$$

$$\text{Copper liberated} = 12,466,660 \text{ g} + 178,340,400 \text{ g}$$

$$\text{Copper liberated} = 190,807 \text{ kg}$$

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