

## Enhancing Gold Recovery using Hydro-Jex<sup>®</sup> at Cripple Creek and Victor Gold Mine Co.

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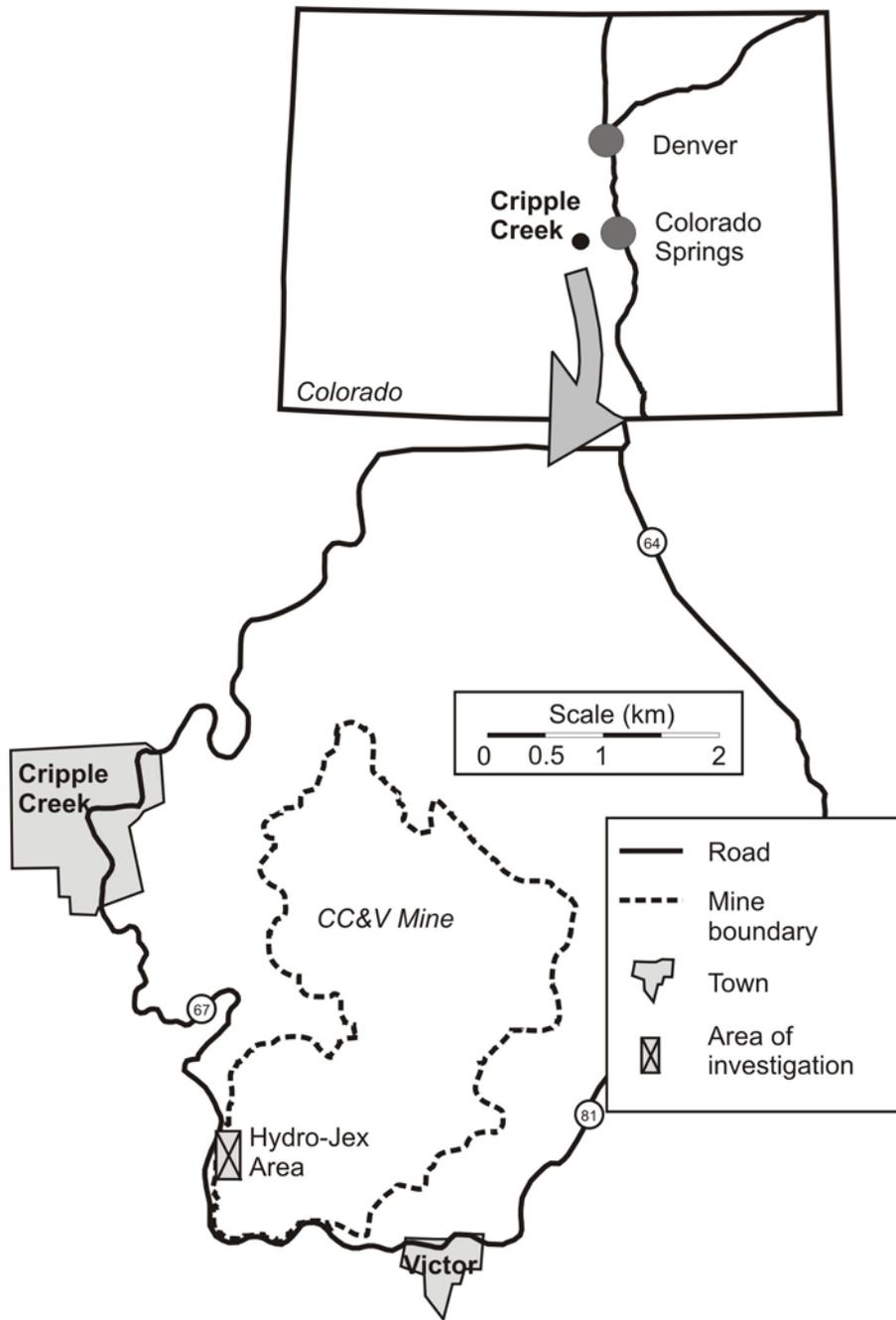
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### ABSTRACT

A trial application of the Hydro-Jex<sup>®</sup> technology was deployed on the Valley Leach Facility at AngloGold Ashanti's Cripple Creek and Victor Gold Mine. Underperforming zones were identified within isolated areas of the heap. Surface-based remediation and recovery efforts were ineffectual because of the extreme depth of the targeted areas. The Hydro-Jex<sup>®</sup> application provided a direct means of delivering leaching reagents to the targeted areas. The project was supported by geophysical monitoring. Time lapsed electrical resistivity monitoring was conducted to help understand the fluid movement within the heap during the injections. The results of the monitoring are presented along with gold production estimates.

### INTRODUCTION

AngloGold Ashanti's Cripple Creek and Victor Gold Mine (CC&V) is located in the historic mining district southeast of Cripple Creek, CO (Figure 1). Operations at CC&V consist of open-pit mining followed by heap leaching on a valley-fill-type heap that provides the sole means of gold production. Heap leaching operations at the Valley Leach Facility (VLF) have been in continuous operation since 1994. The VLF was originally designed with  $0.7 \times 10^6$  m<sup>2</sup> of lined area and one internal pregnant solution storage area. A two-stage open-circuit crushing operation was used to process approximately 24,500 Mt of ore per day to a nominal P<sub>80</sub> of 3.8 cm. The ore was stacked on the heap in 15 m lifts under an ultimate height restriction of 91 m. Several expansion projects and permit amendments have since increased the scope of operations. Ultimately, the lined area has increased to over  $66.5 \times 10^6$  m<sup>2</sup>. Additional solution storage areas were added in 1996 and 2003 and the crushing circuit was upgraded in 2002 to process 65,300 Mt per day to a P<sub>80</sub> of 1.9 cm. The deepest point the VLF is currently over 183 m.



**Figure 1. Location of Cripple Creek and Victor Gold Mine, west of Colorado Springs, CO. The Hydro-Jex<sup>®</sup> well field is detailed in Figure 2.**

Several times during the last decade, CC&V has undertaken extensive pad-wide drilling campaigns. Conceived as a method to directly inspect leaching conditions within the heap and to assess the sagacity of inventory estimates, samples were obtained using sonic drilling and analyzed to assess reagent consumption and residual gold deportment. Data from the 2008 and 2009 drilling programs identified an area on the west side of the VLF that had abnormally high residual grade approximately 100 m below the surface; several samples showed leachable grades in excess of 0.583 g/Mt. Based on ore placed at similar

times elsewhere, the expected grade should have been no greater than 0.017 g/Mt. The results also showed that samples from the area consumed relatively high amounts of lime during bottle roll tests.

A review of ore stacking records indicated that approximately  $1.5 \times 10^6$  Mt of ore obtained from a historic dump had been placed in the affected area in 2001. The ore was essentially waste from a historic mine with grades sufficient to justify placing it on the leach pad, but it also contained a significant quantity of active sulfides that had been oxidizing for several decades. Very little lime was added to this ore when it was placed in 2001 and it was hypothesized that low alkalinity was severely limiting the efficacy of leaching in the area. However, because the area was over 100 m below the current surface of the VLF, transporting additional alkalinity and the necessary reagents to the underleached ore could not easily be accomplished via traditional surface-based secondary recovery techniques.

Few operational techniques exist to truly improve recovery of the passive inventory in large heap leach operations. Secondary recovery methods, i.e., processes used to rework the heap after cessation of the initial leaching cycle, typically involve recontouring of side slopes (Seal and Jung, 2005), ripping (Uhrig and Koons, 2001), and managing solution and reagent delivery strictly at the surface. These methods indirectly promote an enhancement of recovery. However, variations in ore type, particle size distribution and the method of ore placement can give rise to solution channeling (e.g., Orr 2002; Orr and Vesselinov, 2002; Wu et al., 2009; Rucker 2010) severely limiting the efficacy of these surface-based methods.

The key to significantly reducing passive metal inventory in a heap leach pad, resulting from adverse leaching chemistry or simply poor solution coverage, is to promote direct contact of the lixiviant to the location of the underleached ore zones within the heap. This can be accomplished through application of the Hydro-Jex<sup>®</sup> technology (Seal 2004, 2007). The method stimulates metal production by pushing solution deep within a heap from a centralized well. The process mechanically changes the heap by pumping solution at pressures greater than the lithostatic pressure, similar to the enhanced recovery methodologies used in the oil and gas industry. The mechanical changes open up new solution pathways, thereby promoting a direct means of lixiviant contact to the locations of remaining metal inventory that were missed by the initial surface leaching cycle. The technology has been successfully deployed by Newmont Mining Corp. in Nevada with over 100 stimulation wells drilled on several heap leach pads (Seal et al., 2011).

During the summer of 2010 CC&V undertook a trial Hydro-Jex<sup>®</sup> program with the goal of reestablishing favorable leaching conditions and recovering residual gold from the underperforming zone identified in the heap drilling campaigns. The project was supported by geophysical monitoring used to track solution flows within the heap and help understand fluid propagation by timing the arrival of wetting fronts on nearby boreholes at 18 and 24 m away. Observations and insights from the monitoring are presented below along with discussion of the impact of the project on gold production.

## **BACKGROUND**

When a viscous fluid is injected within unconsolidated and noncohesive particulate matter, the flow regime will depend on the ratio of inertial to viscous forces as described by the Reynolds number. At low Reynolds numbers, typically less than one, the flow can be described by Darcy's Law with the hydraulic gradient ( $i$ ) proportional to the seepage velocity ( $q$ ):

$$i = -Rq \tag{1}$$

where  $R$  is the hydraulic resistivity (reciprocal of conductivity). Fluid pressures within the host media in this regime are sufficiently low that the principle effective stress that holds the media rigid is not exceeded and the fluid simply flows away from the injection source as leak off.

When pressures are increased and inertial forces greatly exceed viscous forces, the flow is considered non-Darcian and the gradient is proportional to a nonlinear seepage velocity (Basak 1977):

$$i = -aq^m \quad (2)$$

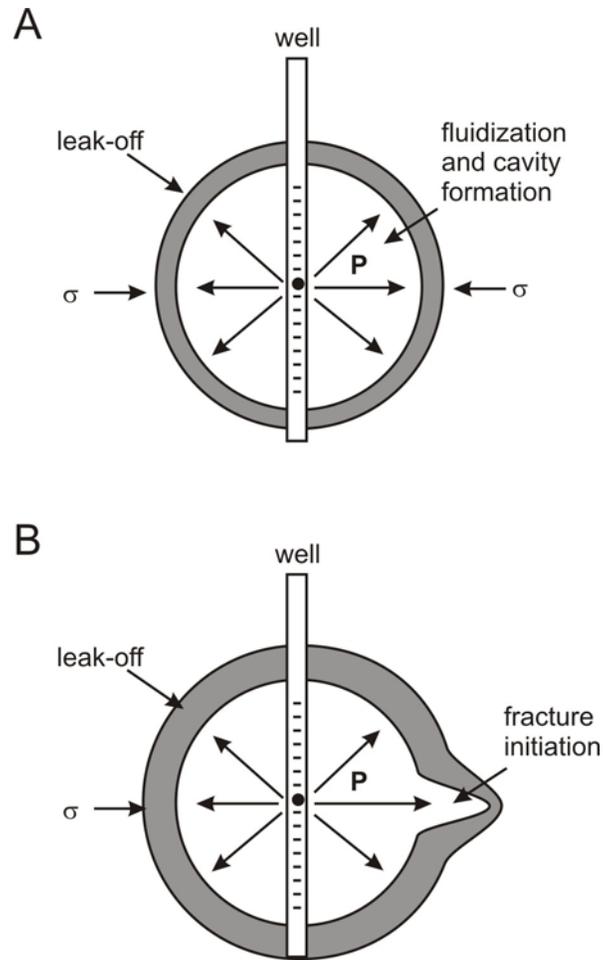
Where  $m$  is a fitting parameter that relates, empirically, the relationship between gradient and velocity, and  $a$  is the hydraulic resistance. At low Reynolds numbers the value of  $a$  approaches the value of  $R$  in Equation 1, but at progressively higher Reynolds numbers, the turbulence itself adds a head loss due to friction (Bordier and Zimmer, 2000), causing the value of  $a$  to diverge from  $R$ . At this stage, the mechanical drag forces imposed by the higher velocity are still too low to move particles away from the wellbore and the pressure is lower than the overburden principle effective stress caused by the weight of the overlying heap. Wu (2006) refers to this as a fixed bed flow.

As pressures are increased further the internal fluid pressures eventually exceed the overburden pressures and the flow regime changes dramatically. Wu (2006) explained that for these pressures and fluid velocities, cavities can form near the injection point, and three stages of cavity evolution can be explained as: (1) cavity initiation in the vicinity of the injection point when the velocity of fluid reaches a certain critical value (a schematic of the cavity formation near the wellbore is shown in Figure 2A); (2) stable cavity development and fracture initiation in response to each increment of velocity increase (Figure 2B); and (3) unstable cavity propagation after the injection velocity reaches a second critical value. Furthermore, Wu (2006) explains that these stages can be explained by considering the drag forces applied to the particles by the fluid continuously seeping through the particle assembly. The drag forces cause particles to move away from the injection point, thus the particulate material is unloaded which causes a tensile volumetric strain in its vicinity. Once this strain reaches a critical value corresponding to the loss of contact between the particles in all directions, a cavity forms. This critical strain value corresponds to the “fluidization” of the particle-fluid mixture (Wu 2006). When the injection velocity increases, the cavity or fracture begins propagating until it reaches a stable state.

## METHODOLOGY

### Hydro-Jex<sup>®</sup> Injection

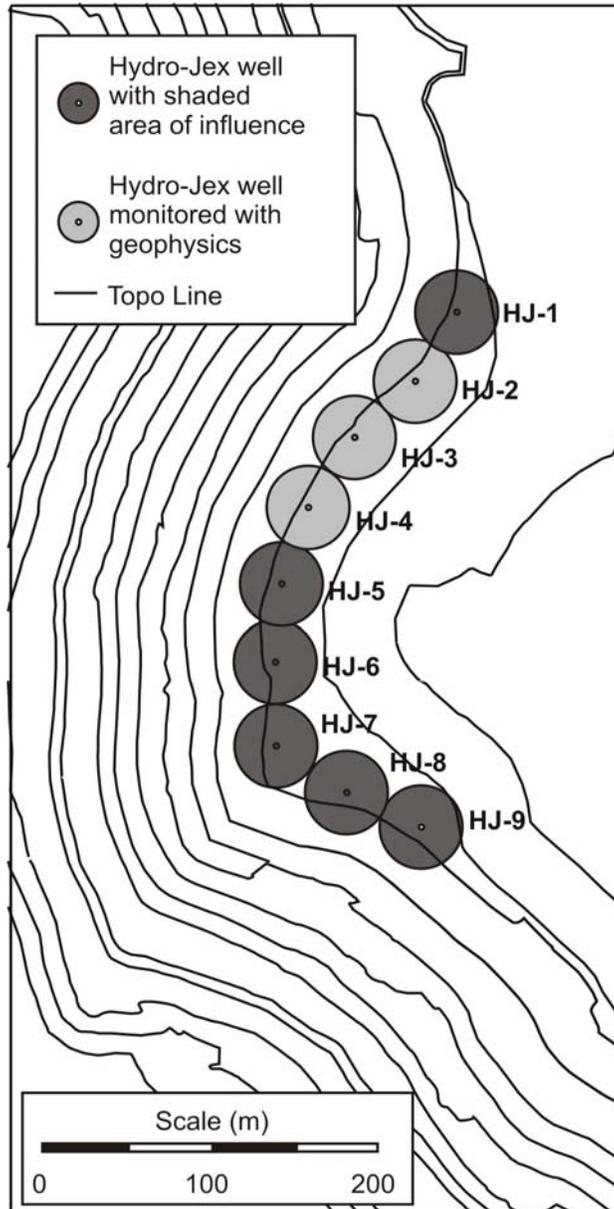
Seal (2007) describes the Hydro-Jex<sup>®</sup> process as a three step procedure. In the first step, steel casings are driven down holes drilled in the heap and perforated at target depths corresponding to locations identified as having high concentrations of residual gold and/or adverse chemistry. Assays on cuttings obtained during the drilling can be used to refine understanding of subsurface conditions; but Rucker (2010) showed that assaying alone may not be adequate for describing the spatial distribution of hydrological and metallurgical parameters and that these parameters can be better described by coupling traditional assays with electrical resistivity characterization. Through a welded wellhead attached to the casing, a high-pressure pump is used to force solution down into the interior of the heap creating new solution paths while adding reagents to targeted zones of underleached ore. A downhole isolation mechanism isolates each zone and controls the depth at which solution enters the heap allowing specific areas to be targeted. Multiple depths can be targeted and treated by repositioning the isolation system. During this stimulation phase, any combination of reagents can be added to the solution pumped down the well to accelerate gold dissolution or remediate any adverse chemical conditions. The final stage of the process consists of periodically irrigating each well with leaching solution to rinse the dissolved gold to the liner and to further enhance chemical changes.



**Figure 2. A) Cavity generation and B) fracture initiation during injection. Figure adapted from Chang (2004). P =pressure and  $\sigma$ =effective stress.**

Nine Hydro-Jex<sup>®</sup> wells were drilled in the VLF ranging in depth from 116 m to 146 m. Figure 3 shows the site and the layout of the wells, with the initial estimated design diameter of fluid penetration approximately 50 m (represented by circles around each well location). Each well had approximately 20 injection zones along its length. Three of the injection wells were monitored with electrical resistivity geophysics. All wells were monitored for pressure and flow rate. The actual penetration within each zone depended on site specific parameters such as depth, hydraulic resistivity, soil cohesion, and injection parameters.

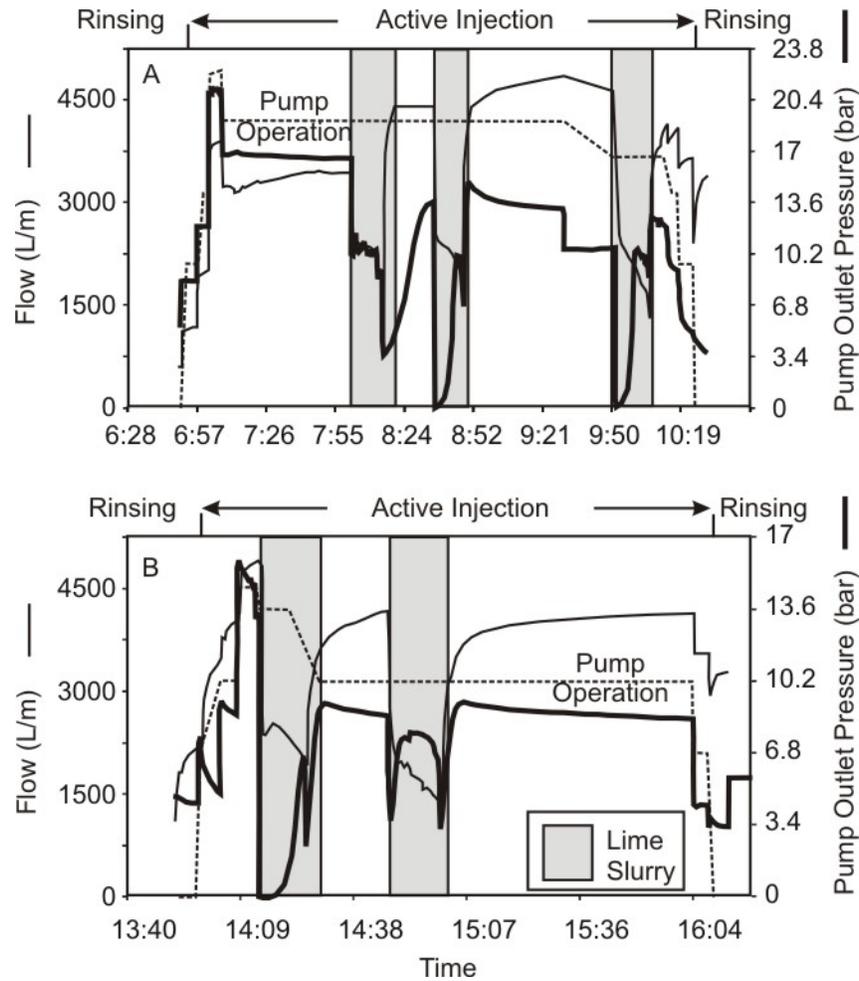
Figure 4 shows results of the injection procedure for two zones in HJ-9, with Figure 4A recording the injection data at a depth of 112 m and Figure 4B at 100 m depth. The data were recorded continuously with a datalogger and manually at the top of the well and include tophole pressure at the pump outlet, flow rate, and pump speed. The bottomhole pressure can be estimated by adding 11.2 bar to the pressures in Figure 4A and 9.8 bar to the pressures in Figure 4B to account for the depth and fluid friction loss.



**Figure 3. Configuration of the Hydro-Jex<sup>®</sup> wells along the western portion of the VLF, showing estimated influence area of each injection. Injections wells HJ-2 through HJ-4 were monitored with electrical resistivity geophysics.**

In Figure 4A, the initial flow before the pump is turned on was about 870 L/min at 5.5 bar line pressure (measured at the top of the borehole). At a few points along the timeline, the pumping is slowed in order to add lime slurry down the hole; pumping was resumed when the lime slurry had been offloaded. At the end of the injection cycle and after the pump is turned off, the flow is increased above the pre-injection values to around 3,020 L/min at 4.2 bar. If no mechanical changes had occurred in the zone such that the hydraulic conductivity (or hydraulic resistivity) was unaffected, then the pressure should have increased proportional to the increase in flow. However, given that the pressure dropped with an increase in flow, this indicates that the hydraulic conductivity increased due to the injections.

In Figure 4B, cavity generation and fracture initiation is observed early in the injection cycle, before the first load of lime slurry was delivered. A drop in injection pressure with increased flow is a characteristic sign of fracture initiation at the critical pressure as described by Wu (2006). This pressure drop is observed multiple times indicating that the fracture actually causes new cavities to be formed before rupturing and fracturing again. During the extended injection period following the lime slurry additions, the flow of barren solution increases to around 4,150 L/min for about an hour while the pressure drops from about 9.3 bar to 8.9 bar.



**Figure 4 (A & B). Injection parameters for well HJ-9, with pressure and flow recorded continuously through a datalogger. Pump operation and lime slurry loads were recorded manually. A) Injection at 112 m and B) injection at 100 m below pad surface. Dotted line represents a normalized pump operation.**

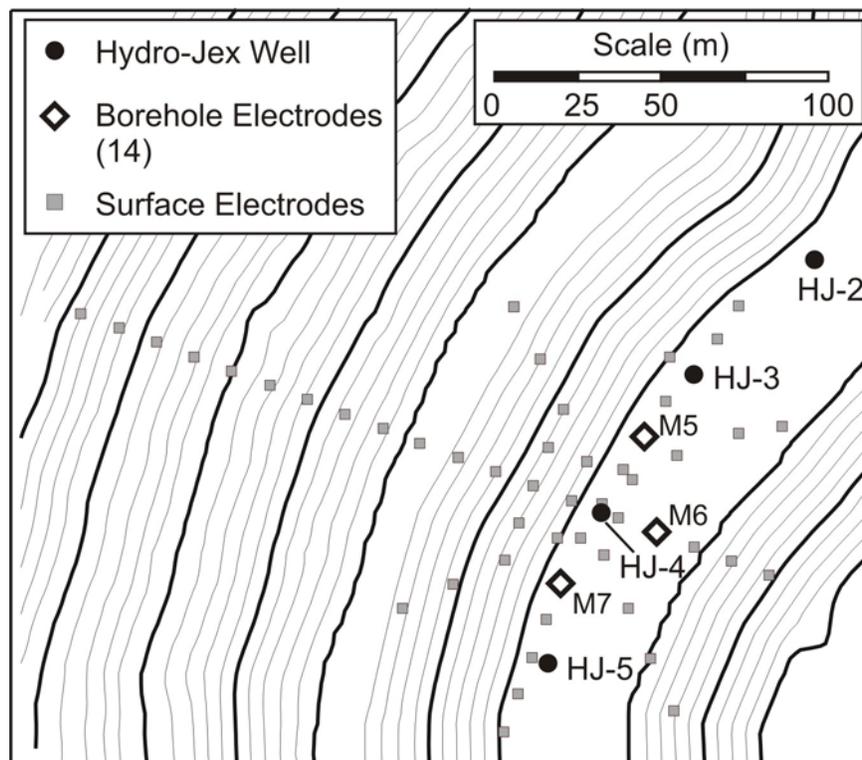
### Geophysical Monitoring

Once injections have started, there are no assurances that the leachate will flow evenly across the stimulation zone. Variations in ore type, crush size, and stacking history all contribute to variations in compaction, and hence, the preferred fracture propagation directions. The only way to determine the solution path is through active monitoring during the injection. This information can be used to optimize the process and maximize recovery from the technology. Hydrologic-based sensors buried in heaps, such as tensiometers (Menacho et al., 2007) or time domain reflectometers (Walker and Powell, 2001) provide one means of capturing solution flow information; but these point-based measurements have to be nested

to cover multiple depths and staged sufficiently around the injection point to ensure complete data capture.

An alternative to the point-based monitoring technology is a volume-based technology that can sense changes far from the sensor. A simple volume-based measurement method includes the geophysical method of electrical resistivity, which provides a parameter that is sensitive to the degree of saturation in a heap. Although multiple parameters can influence the final measured resistivity value (e.g., water content, clay content, porosity, pore water constituents), the change in resistivity over time will necessarily be reflective of the changes in pore space saturation.

An electrical resistivity monitoring campaign was conducted on three of the nine wells to observe the flows from the injections. The sensors for resistivity consist of steel stakes that can pass electrical current or measure the voltage field, and were placed along the surface of the heap (including over the side slope) and within boreholes adjacent to the injection well. Given that the injection well itself is steel, it too was used as an electrode to pass electrical current. Forty-seven electrodes were placed along the surface, which radiated outward from the injection point. An additional 42 electrodes were placed in three boreholes around the well. On the surface the electrodes were nominally spaced 12 m apart, while inside the boreholes the electrodes were spaced 10 m apart. Figure 5 shows the electrode distribution surrounding injection well HJ-4.



**Figure 5. Layout of electrodes for electrical resistivity monitoring around injection well HJ-4**

Each electrode was wired individually to a central data acquisition unit that controlled which pair of electrodes were to receive an electrical charge, while all other pairs measured the resulting voltage. For this instance, the pole-pole array was used where one pole (i.e., electrode) from each electrical current and voltage pair measurements were placed far from the survey site. During fluid injections, each electrode

had a turn at passing current with the remaining electrodes servicing as measuring points before repeating the process over again. A complete cycle of measurements took approximately 30 minutes to complete.

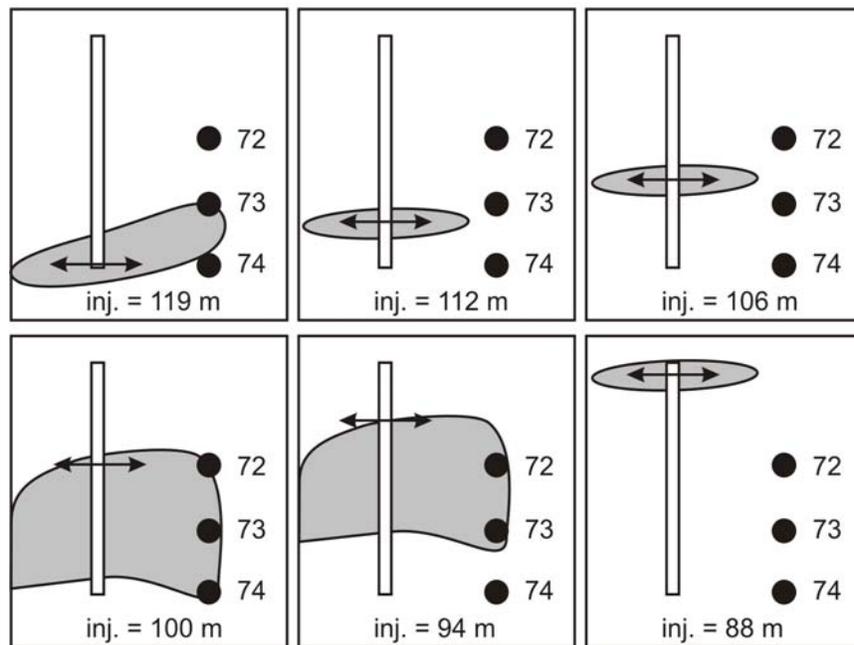
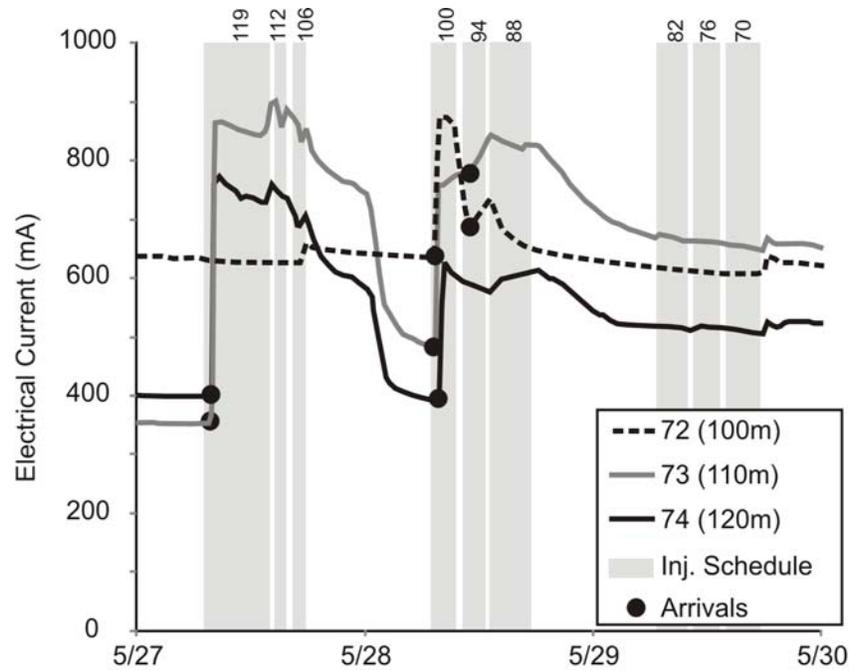
Processing the data occurred in two stages. The first stage was the real-time monitoring of electrical current as a time series. The electrical current was used to benchmark wetting front arrivals of the injected plume at the electrodes, as the current output is a function of the contact resistance the sensor has with surrounding media. If the contact resistance decreased due to the increased saturation, the electrical current also increased according to Ohm's law. Although the temporal resolution of arrival was high, the spatial resolution was quite low. To fill in the gaps between electrodes, the voltage data provided a continuous field of data that would show size and directionality of the plume's path. Plotting the continuous voltage field provided the second level of data processing.

## RESULTS

### Geophysical Monitoring

Monitoring the movement of solution and defining flow characteristics during the injections was one of the primary goals for the project at CC&V. Arrays of surface and borehole electrodes were designed to capture the three-dimensional propagation of the injected plumes through time. In addition, given the nature of the project and the real-time data presentation to assure slope stability, the usual geophysical processing and modeling methodology of inversion, demonstrated in Rucker et al. (2009a) and Seal et al (2008), was not possible. Inversion modeling is a time-intensive process that aims to reconstruct the spatial distribution of the property electrical resistivity from all of the voltage measurement combinations. Instead, the electrical current output from the borehole electrodes were monitored for changes, which could be acquired without further processing. It was clear that an increase in saturation would reduce the contact resistance between the electrode and heap.

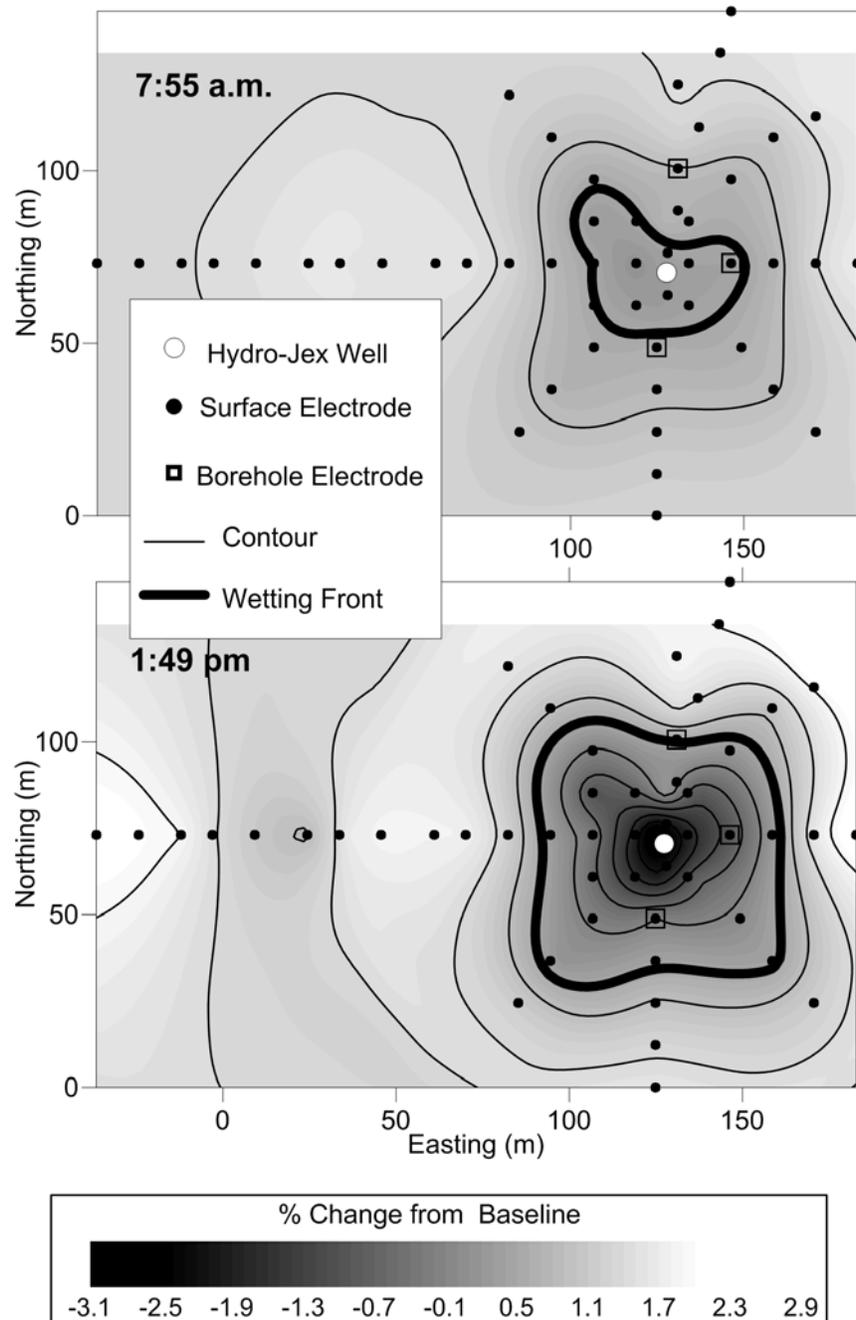
Figure 6 shows an example of the electrical current output from electrodes at 72, 73, 74, in borehole M6 during fluid injection on well HJ-4. Time series current data from three electrodes are shown, corresponding to depths of 100, 110, and 120 m below the surface of the heap. The injection schedule is also overlain on the plot to show the timing of wetting front arrivals at the electrodes relative to the start of each injection. For example, during injection at the 119 m depth, the electrodes at 120 and 110 m registered an arrival (black dot) within 45 min, during which time the current output almost doubled. The bottom portion of Figure 6 shows highly conceptualized plumes from the injection that could be interpreted from these arrival data. In order for the plume to arrive at the 110 m electrode and possibly beyond, from the 119 m injection depth, the pressure from the injection would have to overcome the effective stress and gravitational forces. Throughout the remaining injections for the day the electrical current remained high; suggesting that the saturation levels also remained high. It is unlikely that new plumes arrived from fracturing during the 106 or 112 m injection based on the relative steady values of the current. After cessation of injections for the day, electrical current drops, as vertical drainage becomes the primary mode of solution movement. The following day, the Hydro-Jex<sup>®</sup> injection at 100 m depth registers an arrival at the 100 m electrode in about 18 min, and at the 110 and 120 m electrodes soon after. A large coverage of the injected solution is needed to see this type of response on all three borehole electrodes.



**Figure 6. Time series of electrical current during injection on HJ-4. The timing of wetting front arrivals is shown as a black dot. The bottom series of profiles show highly conceptualized views of the plume at the time of arrival based on the time series data.**

While the time series of electrical current provided a temporal assessment of lixiviant arrivals, assessing the spatial distribution of the arrivals was accomplished by evaluating the voltage potential measured on the surface electrodes during current transmission on the centralized injection well. The voltages were linearly transformed to apparent resistivity (Rucker et al., 2010), compared to a background measurement just before injection began (as percent difference), and plotted as spatially-continuous contours. To pick which contour represents the wetting front, we plotted contours at the time of first arrival indicated by the

electrical current increase from the nearby borehole electrodes. Figure 7 shows an example; where by 7:55 am the lixiviant had arrived at the eastern borehole during injection on the 119 m zone. We then tracked this same contour to understand the area of impact by the injection. Specific to the 119 m injection zone, the wetting front appears to move southward in excess of 30 m. The large lateral spread of the injected lixiviant was abnormal, with most injections propagating 20-25 m radially from the well as demonstrated in other projects (Rucker et al., 2009b).



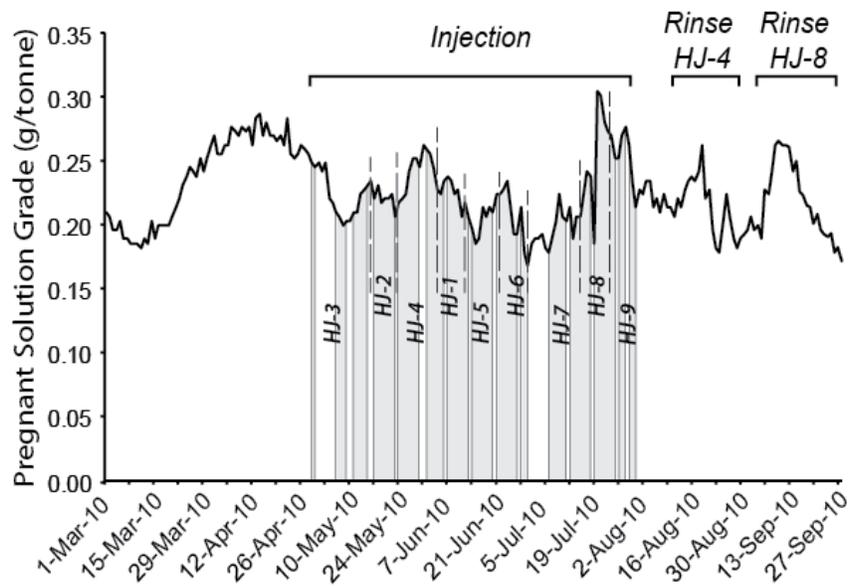
**Figure 7. Apparent resistivity contours presented as percent difference from pre-injection measurements (at 7:10 am) for the injection on the 119 m zone in HJ-4. Position of the wetting front was interpreted from arrivals recorded during electrical current transmission.**

## Gold Production

The VLF features three discrete pregnant storage areas (PSSAs), and each PSSA is supplied by a different region of the heap. The solution grade from each PSSA can be sampled, but the grade represents the average of all solutions reporting from the millions of square feet of lined area within that specific drainage. It is not possible, therefore, to directly sample the solution grade from any subsection of the drainage and hence, it is not possible to directly calculate the quantity of gold produced as a result of the Hydro-Jex<sup>®</sup> project. However, the impact to production can be estimated by comparing trends in the solution grade against those expected from stacking and leaching histories.

Figure 8 shows a plot of the solution grade from the Phase 2 drainage over a period spanning the injection phase of the project. The shaded areas indicate days that injections occurred. From the graph it is clear that the solution was approaching a base grade below 0.18 g/Mt ahead of the startup of the injection project, and that there were several sharp grade increases coincident with the injections. Variations in liner elevations beneath the injection wells and local conditions within the VLF prevent drawing any definitive correlations to the changes in grade, but the trends and magnitudes of the observed changes are consistent with data from drill samples. For example, injections in areas with high residual grades were accompanied by upswings in solution grade soon after. This trend is particularly clear in the last three wells of HJ-7 through HJ-9. In each case there was a solution grade increase approximately three to five days after the initiation of each injection. The lag time corresponds approximately to the time that the injections reached the 88 to 107 m zones, which is the region known to exhibit higher residual grades.

Making the conservative assumption that the pregnant solution grade would have remained at approximately 0.18 g/Mt, an estimated 2,700 troy ounces of gold were recovered during the injection phase of the project. However, it is likely that over 4,300 troy ounces have been recovered from the areas surrounding the injection wells. Each of the Hydro-Jex<sup>®</sup> wells has been subjected to additional rinsing in the months after the injection, allowing time for further leaching of the ore. Typically, each zone is rinsed for three to four days at a targeted flow rate of 750 L/min, with up to four zones in operation at the same time. The protracted upswings in solution grade after completion of the injection phase correspond to rinsing wells HJ-4 and HJ-8. In each case the post-injection production likely exceeded 700 troy ounces of gold. Rinsing is ongoing and recovery from the Hydro-Jex<sup>®</sup> wells is expected to continue for upwards of two years.



**Figure 8. Pregnant solution grade vs. time. Shaded areas denote days with active injections. Time periods for rinsing HJ-4 and HJ-8 are also indicated.**

## DISCUSSION

A pilot-scale, enhanced recovery project was conducted at CC&V to reestablish favorable leaching conditions to isolated zones deep within the heap and to remove residual gold remaining from the primary leaching cycle. The enhanced recovery method, referred to as Hydro-Jex<sup>®</sup>, was facilitated by injecting either barren solution or lime slurry at strategic locations on the west side of the VLF leach pad, at pressures that generally exceeded the lithostatic stress of the overburden rock pile. The project was accompanied by both flow and pressure monitoring, as well as a geophysical monitoring method based on direct-current electrical resistivity. Specifically, the geophysical monitoring was used to help track the solution front as it propagated away from the injection well. The final solution grade, and hence recovered gold, was estimated from the discrete pregnant storage areas based on deviations from expected trends.

It was clear from this project that the physics of solution flow from high pressured injections into an unconsolidated, noncohesive rock pile is not fully understood. Conceptually, it was difficult to consider fluidization and the extreme drag forces on large rock particles necessary for cavity generation near the wellbore, and hydraulic fracture propagation away from the wellbore. Yet the predictive modeling examples of Wu (2006), showing bottomhole pressure dropping despite fluid velocity increases, appeared to qualitatively match field data extracted from the Hydro-Jex<sup>®</sup> dataloggers on several occasions. The pressure drop suggested a yield on the sidewall of the cavity, allowing the fluid to propagate to distances likely unachievable by rinsing alone. The mechanical changes in heap structure were also observed from flow and pressure data immediately before and after the active pumping phases of the injection. The flow increased under lower pressures after active pumping, indicating that hydraulic conductivity increased.

One of the greatest values of the geophysical monitoring was the timing of the arrivals on nearby boreholes, either 18 or 24 m away. The arrivals were timed by observing an increase in electrical current output from the deeply buried electrodes, which was due to a drop in contact resistance. In some instances, wetting front arrivals occurred in as little as 18 min and at elevations above the injection zone. Fast arrivals could mean that cavity generation was minimal and fractures propagated along structural planes of weakness. In a few extreme examples, not shown above, planes of weakness were generated artificially by the lime slurry injections. The viscous slurry likely clogged pores and wetting front arrivals of barren solution were observed at electrode elevations commensurate with the injection elevations soon after the slurry injections ceased. The clogged pores provided a plane on which the barren solution could travel laterally. In other examples, wetting fronts arrived within 45 to 60 min, and appeared diffuse due to multiple electrodes registering a hit almost simultaneously. The electrical current data were also used to track the barren solution as it drained downward through the heap.

Using all lines of evidence, including pressure and flow data from the Hydro-Jex<sup>®</sup> skid, geophysical mapping, and gold production values, several recommendations were generated to help optimize production for the 2011 program. The most substantial recommendation is to decrease well spacing from 48 m to 36 m, based on the fact that most wetting front arrivals occurred at the borehole located 18 m away, but much fewer arrived at 24 m away from the injections well. Secondly, interruption of barren injections for lime slurry creates inefficiencies and promote leak off of fluid away from the injection well. After the slurry injection, it appears to be difficult to reestablish a hydraulic fracture unless it creates a viscous plane of clogged pores, which is undesirable. Therefore, continual addition of a dilute lime solution into the barren solution feed upstream of the pump, without stopping the injection cycle would likely improve lateral coverage of both barren while adding alkalinity to the affected ore. Lastly, it was recommended that more electrodes be placed in boreholes to more fully capture the dynamics of cavity generation, fracturing, and leak off, which would improve the injection process for subsequent years.

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