TESTING INVENTORY DRAWDOWN THROUGH PRESSURE INJECTION IN THE LEACH PAD AT LOS FILOS MINE

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ABSTRACT

A review of historic operating practices of the heap leach pads at the Los Filos Mine, Mexico, revealed periods of restricted cyanide addition, reduced leach time, and insufficient irrigation flow. These issues all led to the buildup of partially leached recoverable gold inventory within the leach pads. Drawing down this inventory represented an opportunity to bring value forward. This paper outlines the strategic initiatives which were implemented as efforts to accelerate the inventory drawdown, including geophysical mapping and pressure injection.

KEYWORDS

Geophysics, Heap, Leach Pad, Injection, Inventory Reduction, Resistivity Scan, Monitoring, Hydro-Jex

INTRODUCTION

Los Filos is a heap-leach operation located in the Guerrero gold belt in southern Mexico. Operational and hydraulic challenges at the Los Filos Mine have led to a buildup of gold in inventory within the leach pads. Operationally, periods of restricted reagent addition, reduced leach time, and insufficient irrigation flow have compounded over the last eight years, and resulted in significant inventory growth. Hydraulically, the leach pad has issues with low permeability and solution channeling due to the fines and clay content of the ore. The leach pad is storing high-grade pregnant leach solution (PLS) as perched aquifers above areas that are compacted and difficult to drain. These operational and hydraulic challenges made it particularly difficult to spatially predict the precise locations of the inventory build-up.

Fortunately, the challenges at Los Filos are not unique to the mine, and others have taken steps elsewhere to reduce metal inventory through a program that targets areas for inventory drawdown. For example, Ghorbani et al. (2016) noted that a method of injecting barren reagent solutions, applied directly to specific areas of a leach pad to reduce inventory, was presented by Wan and Brierley (1997) and Wan (1997). Seal (2004; 2007), Seal and Jung (2005), and Seal et al. (2012) have put the injection methodology into practice in Nevada and Colorado gold mines with a technology called Hydro-Jex®. The goal of Hydro-Jex has been to supply reagents at a high pressure over a short duration, followed by periodical low pressure rinse periods to remove leached metal and resupply fresh reagent to the ore.

Up until now, there has not been a clear demonstration on the effects of gold liberation during high pressure injections. The goal of this paper is to show the results of the sub-surface injection program carried out in the leach pad at the Los Filos Mine. The project began with a geophysical characterization program to identify areas of interest (potential inventory 'hot-spots'), followed by drilling and assaying of ore samples to further define the inventory resource in the pad. A well field was then designed that included both injection and monitoring wells. These wells were placed in a test area of the leach pad to target two distinct types of inventory: 1) partially leached and compacted ore, and 2) perched PLS above compacted ore. Monitoring during each injection verified that sub-surface cyanide concentrations could be sustained for a period of time for effective leaching of all lifts stacked at depth. Further use of geophysical methods verified the lateral coverage and area of influence of each injection, which was shown to be sufficiently large to warrant upscaling to other parts of the pad. Finally, gold grades downgradient of the injections were two to three times higher than that of the PLS reclaim pond. Based on these findings, the injection test has been upscaled across other parts of the leach pad in an effort to further drawdown the residual gold in inventory.

SITE DESCRIPTION AND GEOLOGY

The Los Filos Mine consists of two open pits (Los Filos and El Bermejal) and one underground mine (Nukay) with common heap leach, wet plant, and ancillary facilities. Low-grade ore goes to run-of-mine (ROM) truck dump stacking, while high-grade ore reports to the crushing plant and is placed onto the leach pad by a radial stacking system. Although cement is added to the crushed ore, the agglomeration system has not been utilized since the inception of the project. Los Filos is located in the Nukay mining district of central Guerrero State in southern Mexico. The mineral deposits are considered to be intrusion-related gold-silver skarn deposits. Tertiary granodiorite stocks were emplaced into the cretaceous carbonate rocks of the Morelos-formation, forming metasomatic halos at the intrusive contacts. The mineralization is hosted by, or spatially associated with, marble and skarn alteration formed during contact metamorphism of the carbonates. Massive magnetite, hematite, goethite, jasperoidal silica, with minor associated pyrite, pyrrhotite, chalcopyrite, and native gold typically occur in the veins and metasomatic replacement bodies that developed at the contacts between the carbonate and intrusive rocks.

METHODOLOGY

Electrical Resistivity Characterization

Assuming that the solid mineral grains comprising heap leach ore have relatively low electrical conductivity, the flow of electricity through a heap leach pad will be much like the flow of water (Rucker, 2010). Thus larger, interconnected, water-filled pores provide a conductive medium for electrical current flow. Lower water content and/or reduced pore space interconnectivity will be more electrically resistive due to the more tortuous paths that the electrical current must take. Since the primary pathway for electrical current is through solution in the pore space, it is described as being electrolytic. Electrical conductivity of the solution is directly correlated to the dissolved ion concentration.

There are many published studies using the electrical resistivity method to image engineered rock piles (Rucker et al., 2009; Placencia-Gómez et al., 2010; Grangeia et al., 2011; Zarroca et al., 2015). In each case, field data are generally acquired using an established electrode array. A four-electrode array employs electric current injected into the earth through one pair of electrodes (transmitting dipole) and the resultant voltage potential is measured by the other pair (receiving dipole). Estimating resistivity is not a direct process. When current (I) is applied and voltage (V) measured, Ohms law is assumed and resistance is calculated. The ratio of the observed potential to the transmitted current is called the transfer resistance (R). Once the resistance data are collected on a large number of electrode pairs, resistivity models are created with an algorithm called tomography (Loke & Barker, 1996).

At the Los Filos Mine, electrical resistivity data were acquired along a series of parallel transects that varied in length from about 500 m to 1200 m, but were generally placed 75 m apart. The resistivity survey was designed to image down to the liner; the liner's depth was over 70 m in some areas of the leach pad. Figure 1A shows the locations of the resistivity lines across a portion of a leach pad; the survey area was approximately 47 hectares. Although the survey data were acquired as two-dimensional transects (Figure 1B), all data were geo-referenced and collated into a three-dimensional block model and the tomography code RES3DINVx64 was used to reconstruct the electrical properties continuously across the leach pad, similar to what was conducted in Rucker (2015).
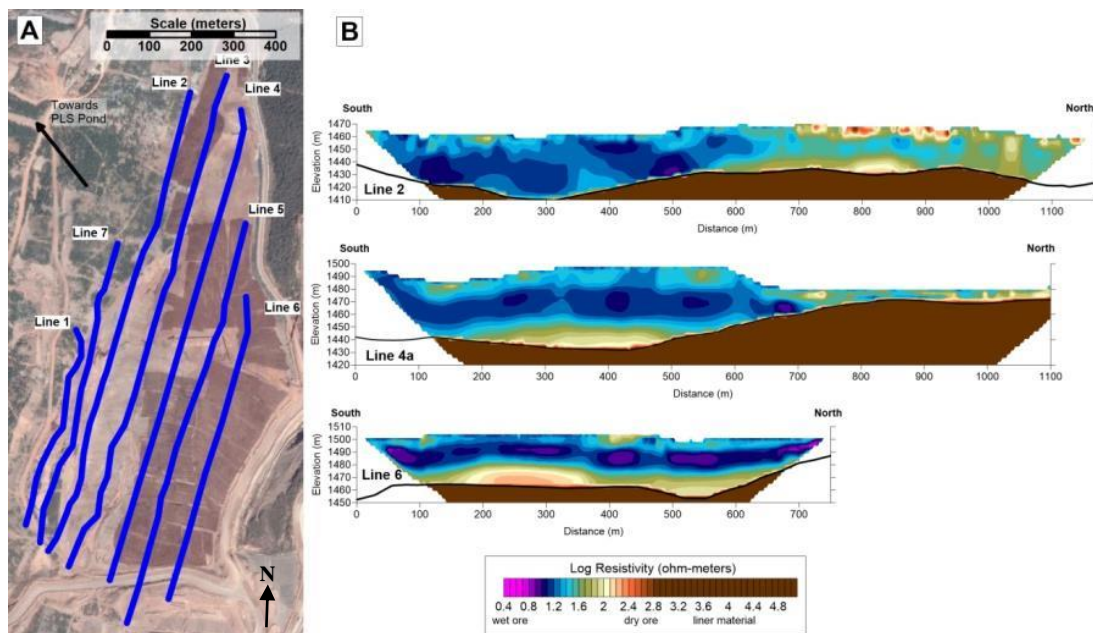

Figure 1. Electrical resistivity survey across a leach pad at the Los Filos Mine. A) Survey line locations, marked in blue. B) Results of three resistivity lines, shown in profile view. The black line demarcates the liner location.

Pressurized Heap Injection

The key to significantly reducing passive metal inventory in a heap leach pad, resulting from adverse leaching chemistry or poor solution coverage, is to promote direct contact of the barren cyanide solution to specific locations within the heap (Seal et al., 2012). The Hydro-Jex technology supplied by Metal Recovery Solutions (MRS) was selected as the pressure-injection system. The Hydro-Jex method horizontally pushes solution deep within a heap from a centralized well through targeted down-hole perforated zones. The process geomechanically changes the heap's structure by pumping solution at pressures greater than the lithostatic pressure (Winterton and Rucker, 2013), thereby fluidizing the material around the injection zone.

Mechanically, the injection occurs from an injection skid that is located between the barren line and injection well. The pumping skid draws solution in and increases flow up to 300 m^3/hr and increases pressure up to 10 to 20 bar. Figure 2A shows a photo of the setup, with the skid, injection well, and barren line. If needed, the barren solution can be augmented with an additional reagent, such as calcium hydroxide or other pH modifier. Within the well itself, an isolation mechanism is lowered to specific depths, where barren solution can be directed within zones (Figure 2B); wells at Los Filos had injection zones spaced every 6 m down the hole starting at 10 m below surface. Injections typically lasted two to three hours per zone before moving to the next zone within the injection well. This high-pressure injection phase is referred to as 'zone stimulation'. Within a week after stimulation, low-pressure rinsing was performed on each well at 10 to 50 m^3/hr and 0 bar for extended periods of time. The total rinse volume can easily exceed 10 times that of the initial high pressure injection.
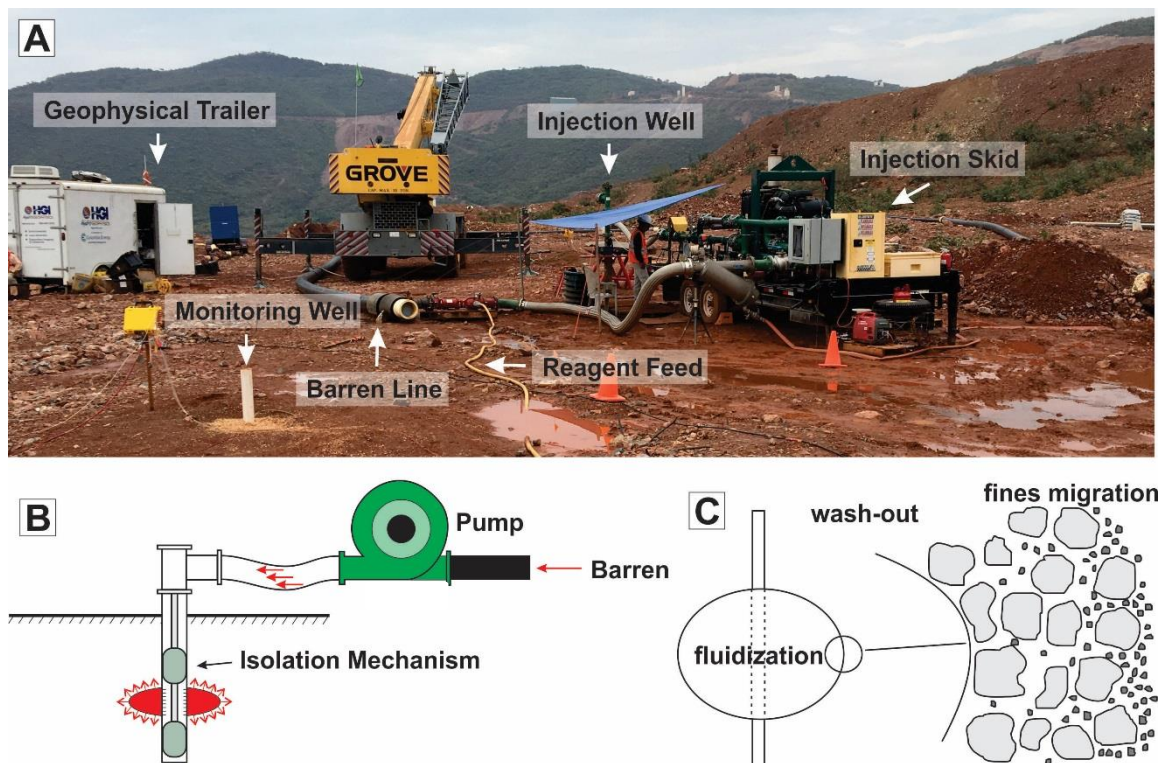

Figure 2. Hydro-Jex setup for pressurized injection into a heap. A) Photo of site logistics for injection and monitoring. B) Schematic of injection mechanism. C) Schematic representation of fluidization and washout of fines near the wellbore.

The high pressures within the formation will fluidize material near the wellbore. Wu (2006) showed that drag force-induced fluidization can create a cavity in the particulate assembly and move finer

grained material out of the immediate area near the well. In this framework the critical velocity for cavity formation is dependent on the viscosity of the injection fluid. At low fluid viscosities energy dissipation in the fluid is mainly due to turbulence and cavity growth, and is governed by the confining stress state. Observations (Winterton & Rucker, 2013; Rucker, 2015) concur with predictions from the fluidization conceptual model and imply that fines near the injection zones have been 'washed-out' leaving a string of highly permeable regions along the lengths of the well bores. The illustration in Figure 2C shows a cross-section along a hypothetical well depicting the wash-out concept (adapted from Winterton & Rucker, 2013).

Injection Monitoring

To validate the test objectives of meeting flow, grade, and safety requirements, a robust monitoring program was designed to measure multiple aspects of the heap during injection. The monitoring included parameters to understand hydraulics of sustained injection using total volume of barren solution introduced to the heap, in situ resistivity, and water levels. The photo of Figure 2A shows the geophysical monitoring trailer, which acquired time lapse resistivity data for tracking the position of the barren solution front (injection plume) deep within the heap. A monitoring well is also shown that was used for both measuring the water levels and extracting PLS for metallurgical analysis. For metallurgical analysis, the following parameters were measured: pH, free cyanide, and the concentration of gold, silver, and copper. An example of the conceptual model with an injection well and downgradient monitoring wells is shown in Figure 3. The monitoring wells were constructed with long screens, filter material, and electrodes for resistivity monitoring.
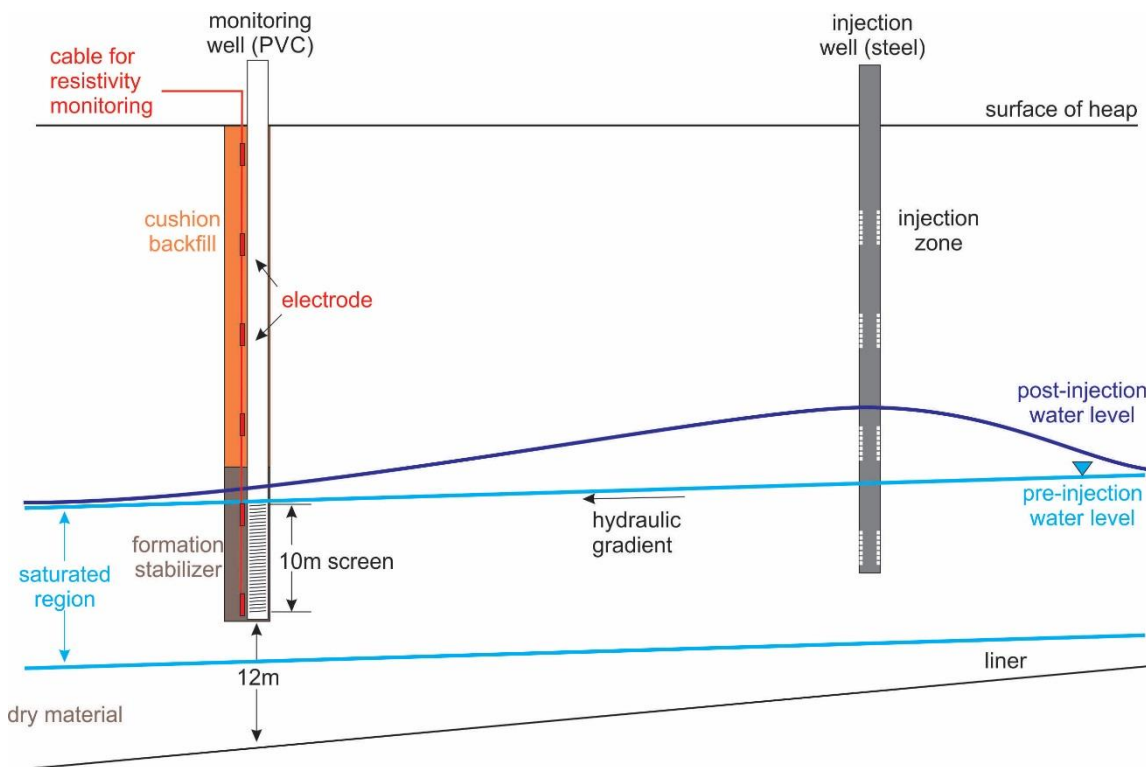

Figure 3. Conceptual model of injection at Los Filos with an upstream injection well and a downgradient monitoring well.

RESULTS

Electrical Resistivity Characterization

Electrical resistivity has the ability to spatially image the heap to discern hydraulic structure that may have resulted from undesired flow patterns, such as ineffective drainage. From past work on gold and copper mines, it has been shown that electrically conductive PLS will provide a strong target for mapping with the resistivity method. Figure 1B shows examples of the resistivity data across three of the lines on the Los Filos leach pad. The electrical resistivity data are color contoured to show the wetter and more conductive material at the low end of the scale (in purple and blue). The drier and more resistive material is shown at the high end of the scale (shown in greens and yellows). The data coverage for each line is down to the liner, shown as brown. Although the liner is a thin plastic membrane, the models show the liner as thick resistive feature. This feature was not included in this analysis. Moving westward, from Line 6 to Line 2, we see a thin conductive layer nearer the surface that gradually thickens and drops to the liner (Figure 1B). In the east, this thick conductive layer sits atop a resistive layer. Again from previous experience, conductive layers on top of resistive layers can be interpreted as a moist region or perched aquifer above compacted material with little to no drainage. In this case, the drainage of PLS appears to cascade over the resistive layer on the west side, likely leaving the ore in the east dry near the liner. When the resistivity data are tied together with a 3D model and sliced, the data show greater continuity. Figure 4A shows a depth slice at about 40 m from the upper most surface. The continuity of the electrically conductive body is now more obvious. From these data, a potential perched aquifer is interpreted (outlined with a dashed line) around the contour of 20 ohm-m (i.e., log transformed resistivity of 1.3). Water level data taken from monitoring wells prior to injection confirm the presence of a perched aquifer (Figure 4B).
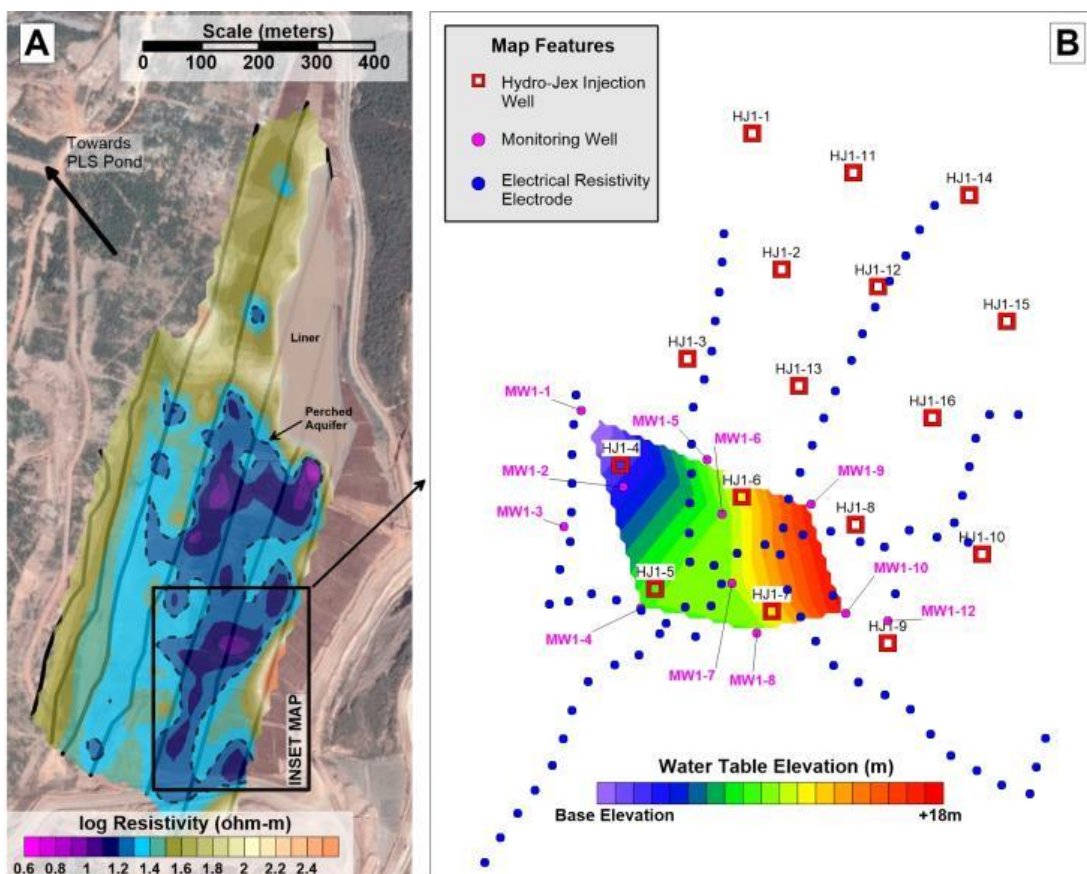

Figure 4. A) Three-dimensional resistivity results, shown as a slice at 40 m below the upper most surface. B) Inset map showing well field design and measured water table elevation

From the resistivity data, a well field and well design for both injection and monitoring wells were created. The well field was placed in an area of the heap that was revealed to have both a water table (trapped PLS) and dry compacted ore (no lixiviant contact); Figure 3 shows a generalized model of this system and Figure 4B shows the specific well layout at Los Filos. The injection wells were separated by 50m and completed to within 12 m of the lower liner. From these 16 injection wells, there were 74 injection zones. In the southern portion of the well field, monitoring wells were generally offset at 10 and 20 m from the injection wells.

Heap Injection and Monitoring

As an example of the information acquired from the injections, results of the hydraulic and metallurgical data during injection on well HJ1-6 are presented in this paper. This well is located in the center of the well field, at the north end of the water table map in Figure 4B. The well's location was such that the lower two injection zones (at 40 m and 34 m depth) were in the compacted (dry) ore, while the upper injection zones (at 27 m depth) were in contact with the perched aquifer. The first injection occurred at approximately 40 m depth, followed by a second injection at a depth of 34 m. The injections lasted for about three hours each with roughly 700 m^3 of barren cyanide solution added to each zone. Figure 5A shows the coverage of solution at the end of the three hours for both injections using electrical resistivity geophysics. The data are presented as a percent change in resistivity between a baseline snapshot acquired before injection started and a final snapshot acquired immediately after the pump on the injection skid was turned off. The two bodies in Figure 5A represent the solution coverage at the 40 m injection zone (brown, opaque) and the 34 m injection zone (tan, transparent). For reference, the injection zones are shown as gray cylinders around the black injection well with purple monitoring wells surrounding the injection area. The screens on the monitoring well are 10 m. For these injections in compacted material, the distribution of solution is offset from the injection well and slightly elongated in a north-south direction. The long axis of the ellipsoid measures approximately 40 m across and the short axis measures 26 m, giving an average radius of influence of 16 m. Given the proximity to the liner, this solution will likely sink to the liner.

The results in Figure 5B show the coverage at the end of a 2.5 hour injection at 27 m depth (zone), which is at the elevation of the perched aquifer. The shallower injection added approximately 570 m^3 of barren cyanide solution in the heap and the figure shows a broader coverage of solution because of the moving plume in the perched aquifer.

As confirmation of the solution coverage in both examples of Figure 5, Figure 6 shows metallurgical data (gold and free cyanide) assayed from solution samples taken from three monitoring wells. MW1-6 is 10 m away from the injection well and MW1-4 is 60 m from the injection well. Both wells are hydraulically downgradient from the injection well. Monitoring well MW1-9 is 27 m upgradient from the injection well. In Figure 6, the injection periods and injection depths (zones) are represented by gray bars. The metallurgical data show that very little change occurs in MW1-9, suggesting that no new barren solution travels upgradient; all solution movement is downgradient from injection. During injection at the 40 m zone, neither barren cyanide nor gold grade change in the two wells downgradient, suggesting that the coverage is more localized to the injection well. The injection at 34 m depth, however, shows a large change in both free cyanide and gold at MW1-6, where a pulse of cyanide travels through quickly followed with a drop in gold grade. Monitoring well MW1-4 does not respond to the injection at the 24m zone on HJ1-6.

The injection at the 27m zone occurs towards the end of the day. By the end of the injection period, the assay data on MW1-4 is shown to change with an increase in cyanide and decrease in gold grade. This confirms the recreated plume from the resistivity model. The decrease in gold grade is a dilution effect from the pulse of fresh cyanide and it is observed from both the 27 and 34 m injections. The following day, when injections resume at the 27 m zone, we see that the gold grade increased in MW1-6, reaching values that exceed the grades prior to injection by mid-morning. In MW1-4, however, the gold and cyanide remain low likely because of the continual flushing that occurs from the perched aquifer.
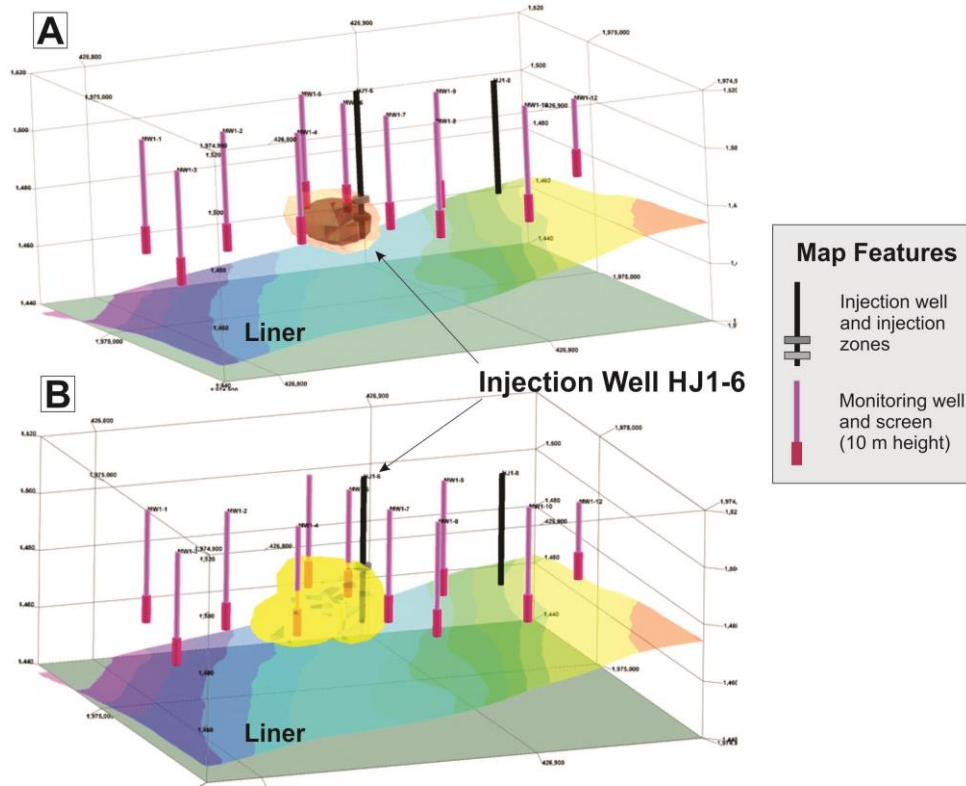
Figure 5. A) Three-dimensional resistivity results for the injection at 40 m and 34 m on well HJ1-6. B) Three-dimensional resistivity results for the injection at 27 m.
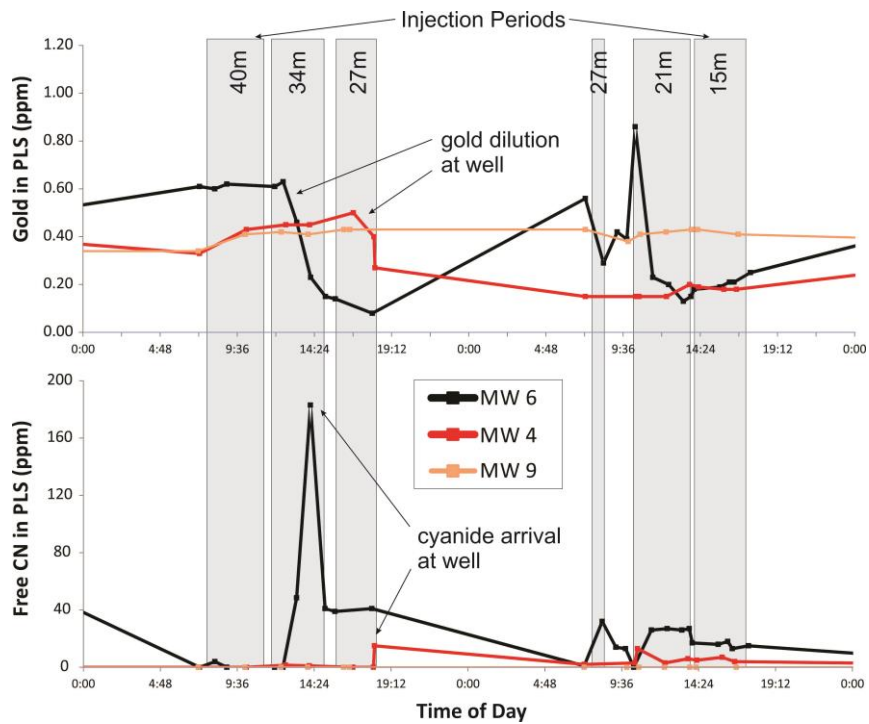

Figure 6. Assay data from three monitoring wells near the injection well HJ1-6.

RECOVERY ESTIMATES

To estimate the amount of gold recovered from the injection test, a time weighted analysis (TWA) can be conducted. The TWA calculates the total gold produced by integrating the curve representing the daily gold production. The curve of daily gold production assumes that the gold mass calculation can be simply made by multiplying the injection volume for the day (combination of stimulation, rinsing, and surface re-leaching) by the average gold grade for the day (from the monitoring wells), *i.e.,* volume multiplied by concentration equals mass. Prior to injection, the average in-situ PLS grade from the monitoring in the area was approximately 0.19 ppm Au. Figure 7 shows the average PLS gold grade curve (average of all the wells) over the duration of the trial program. The average gold grade for each day assumes that this grade is representative of all the PLS in the well field, and is shown to increase during zone stimulation. Based on these measurements, the results of the TWA analysis suggested that approximately 7,000 oz Au were liberated from this injection area over the four month trial.
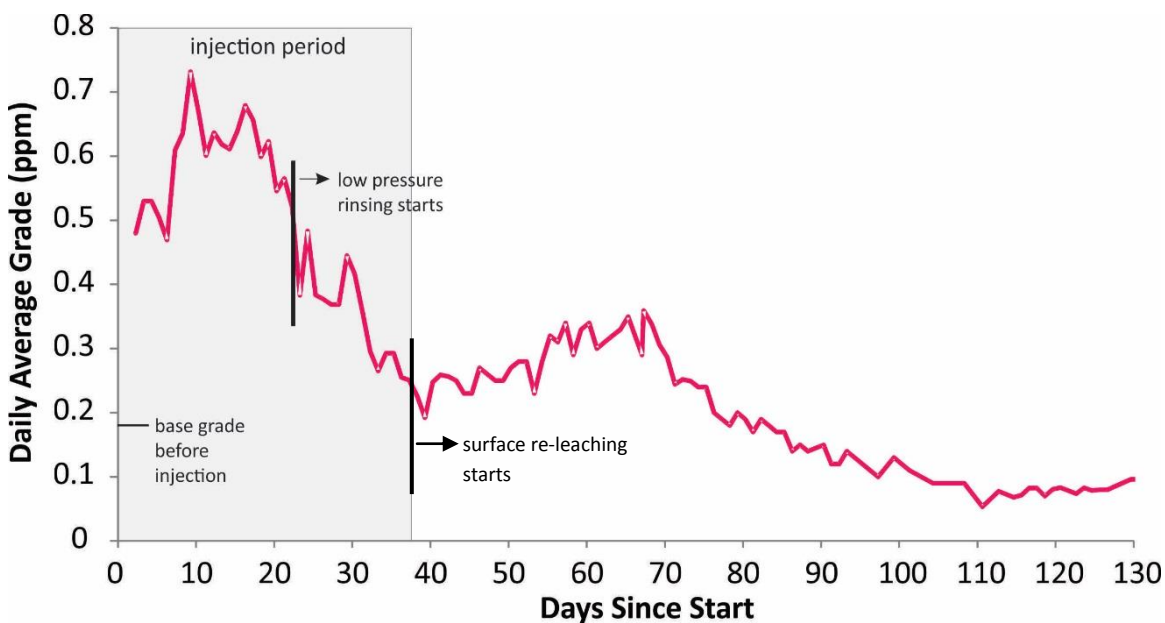

Figure 7. Average PLS grades across all wells.

CONCLUSIONS

A pressure injection trial through the Hydro-Jex technology was applied on a portion of the Los Filos heap leach pad to test whether the technology could help draw-down built up gold inventory. A total of 16 injection wells and 12 monitoring wells were used in the test program. The monitoring covered the high-pressure stimulation, low-pressure rinsing, and surface re-leaching phases of the program. The geophysical monitoring demonstrated the hydraulic mechanisms that controlled the spread of the solution as it entered either compacted regions or a perched aquifer, and validated the area of influence delivered by each injection. The area of influence was determined to be 16m for injections in the compacted ore below the perched aquifer zone. Metallurgical data from solution samples near the point of injection were used to keep track of cyanide concentration and gold production. Results from the TWA analysis suggested that approximately 7,000 oz Au were liberated from the injection area over the four month trial. Based on this successful test, engineering parameters have been developed to scale up across large portions of the leach pad. The results showed that elevated free cyanide levels could be sustained in target areas within the pad, and that pressure injection can be utilized to successfully draw-down built up leach pad inventory.

ACKNOWLEDGEMENTS

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