Dewatering of a Deep Shaft in a Complex Hydrogeologic Setting

Michael Gabora[1], Phillip Brown[2], Hank Ohlin[3], Korin Carpenter[3] and Greg French[3]

1. *Ausenco, USA*
2. *Independent Consultant, USA*
3. *Nevada Copper, Inc., USA*

ABSTRACT

The Pumpkin Hollow Project proposes to mine high-grade, Iron Oxide Copper Gold (IOCG) deposits within a porphyry copper and skarn district in the State of Nevada, United Sates. It is estimated that the district-wide mineral inventory is over 24 billion pounds of copper. As part of the Phase I underground mine, a 655 meter deep exploration shaft is being advanced to exploit a proven and probable reserve of 27.6 million tons of 1.5% copper with associated gold and silver. Existing hydrogeologic data suggested that substantial groundwater inflow would not occur until intersecting a low-angle fault at a depth of approximately 430 meters below ground surface known as the Flat Fault. A dewatering well and observation wells were initiated when water inflows were greater than the shaft excavator's grout program could mitigate. A 457 meter deep dewatering well (DW-1) and three multilevel vibrating wire piezometers (VWPs) were installed near the shaft as part of a staged approach to dewatering. Monitoring data from the first 40-days of DW-1 operation, in combination with the VWP and shaft inflow data, were used to calibrate a mine scale groundwater flow model. The model was used to locate a second dewatering well that was constructed to further minimize inflow and depressurize the Flat Fault during shaft construction. Subsequent testing and analysis of this second dewatering well (DW-2), additional packer testing and geophysical logging resulted in a significantly different hydrogeological conceptual model in the shaft area and as a result, different groundwater flow model results. The project highlights the utility of a well-designed, site specific hydrogeologic characterization program for major mine development.

Keywords: groundwater, dewatering

INTRODUCTION

The Pumpkin Hollow property is located 8 miles southeast of Yerington, Nevada. Four of the five known copper deposits on the project are currently in pre-development with drilling and engineering studies being conducted by Nevada Copper Corporation and an exploration shaft has been advanced in the East deposit (Figure 1). The Pumpkin Hollow Project is in the Basin and Range Province of western Nevada, just east of the Sierra Nevada. The site lies in eastern Mason Valley, bounded on the west by the Singatse Range and on the east by the Wassuk Range. The climate is arid, with hot summers, relatively mild winters, and mean annual precipitation ranging from approximately 101 millimeters at the lowest elevations to 406 mm at the highest.

Extensive hydrogeological studies were completed on the property and the immediate area of the proposed shaft was considered adequately characterized. In November 2013, significant groundwater inflows were encountered as the shaft excavation advanced beyond the static groundwater elevation in an andesite sill unit. Prior hydrogeologic characterization suggested that groundwater inflow through low permeability Tertiary volcanic rocks would be minimal until a low-angle normal fault (the Flat Fault) was encountered at approximately 430 meters (m) below ground surface (bgs). In order to mitigate groundwater inflow into the shaft a grouting program, a hydrogeologic characterization program and initial dewatering works were initiated.

This paper details the enhanced hydrogeologic understanding gained during dewatering and hydrogeologic studies to decrease inflow into the shaft and depressurize the Flat Fault. Additional characterization of the surrounding bedrock improved the ability to predict groundwater inflow into the Phase I underground mine and design appropriate dewatering infrastructure. This project demonstrates the necessity to elucidate hydrogeologic complexities in mine areas to effectively predict inflows and design appropriate dewatering and depressurization programs and explores variability in the effectiveness of two grouting programs.

Geologic Setting

At the project site, a thin veneer (0 to locally 150 feet) of Quaternary unconsolidated sand and gravel (Qal) covers most of the surface. Bedrock is exposed in the periphery of the site primarily as Tertiary volcanic rocks (tuffs) and underlying Mesozoic formations. The Mesozoic section is comprised of carbonaceous calcareous argillites, tuff, and limestone intruded by granitic dikes and sills. These rocks transition locally into skarn, marble, and hornfels with associated copper and iron mineralization forming the five separate but associated deposits; the North, South, Southeast, East, and E2. The deposits are blind with no outcrop and were discovered by aeromagnetic methods and subsequent drill delineation. A geologic model was developed from drill data without the advantage of projected surface geology.

A series of low-angle normal faults separate the Tertiary from Mesozoic rocks (Figure 2) and are zones of 15 to 50 m of enhanced fracturing, breccia development, and variable clay gouge. A pair of generally NNW-SSE trending normal faults bound a graben that down-drops the Tertiary and Mesozoic sections through the middle of the site.

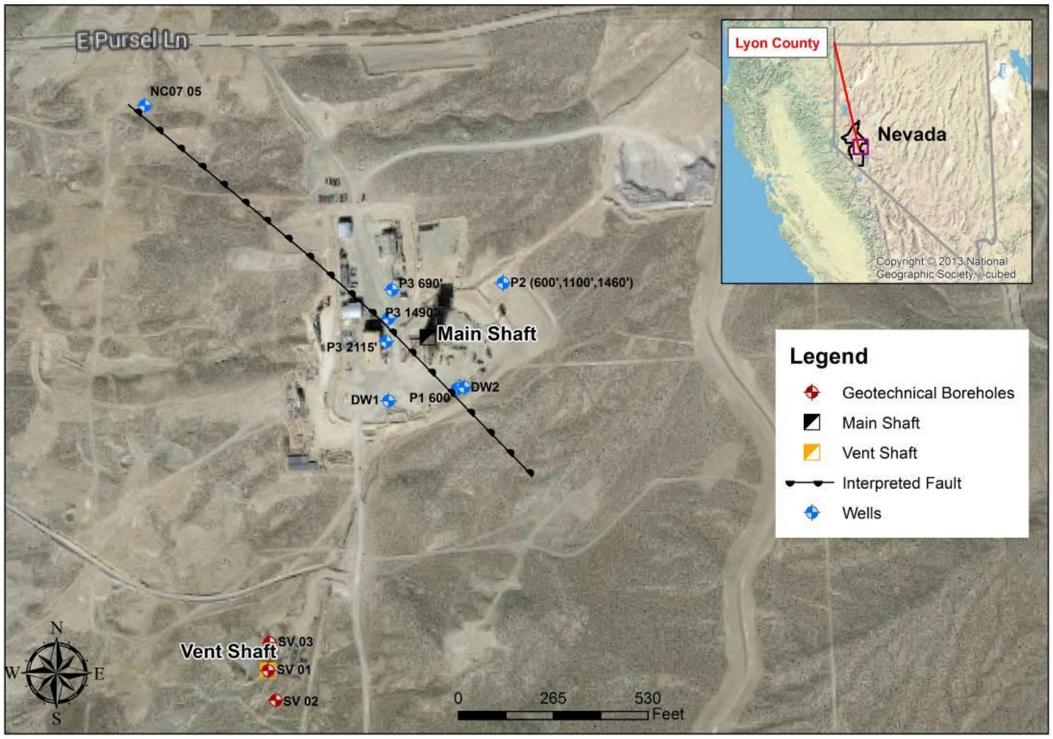

Figure 1 Project Location and Shaft Area Features

Mine Area Hydrogeology

An extensive hydrogeological characterization program was completed for the proposed mine including reviewing core data, testing of 34 boreholes to determine geothermal gradients, installation of monitoring wells and vibrating wire piezometers, packer testing in 3 boreholes, 5 injection tests, 3 slug tests and 2 air-lift drawdown and recovery tests and aquifer pumping tests on 2 wells. Groundwater occurs within the bedrock at a depth of approximately 100 m to 135 m bgs and flows toward the north and northwest, paralleling the flow of the Walker River valley. The bedrock is of generally low hydraulic conductivity except where fracture networks create secondary permeability and transmit groundwater.

Mean mine area estimates of bulk hydraulic conductivity for the Tertiary and Mesozoic bedrock are 1×10^{-2} m/d and 1×10^{-1} m/d, respectively. Tetra Tech (2012) reported that the Flat Fault had elevated hydraulic conductivity relative to the Tertiary and Mesozoic rocks with a mean of 4×10^{-1} m/d.

Calculations using the Maxey-Eakin method to estimate precipitation-derived recharge, based on precipitation estimates made by the USGS Precipitation Zone Method, indicate recharge is zero in the mine area (Tetra Tech, 2012). Stable isotope and 14C data suggest the last recharge to the Flat Fault occurred more than 30,000 years ago. Given the limited recharge potential, identifying lateral connectivity of the Flat Fault and other permeable horizons are considered critical to predicting groundwater inflow and related pore pressure responses in the bedrock. At property wide scales Tetra Tech (2012) used aquifer testing responses and geologic data to conclude that most faults are hydrologic boundaries interpreted to impede groundwater flow across the fault plane and thereby tend to act to compartmentalize the flow system.

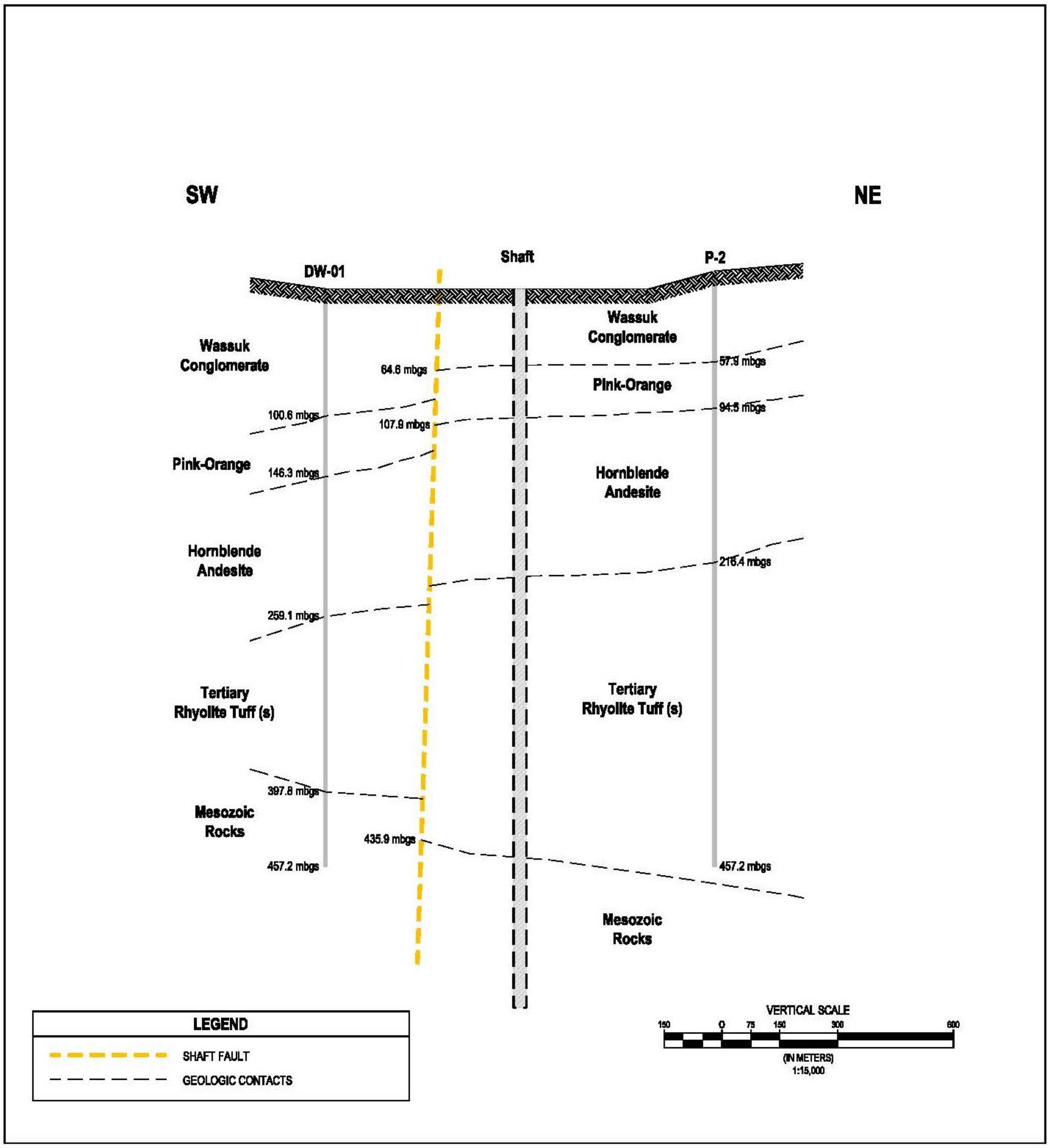

Figure 2 Geologic cross-section in the vicinity of the shaft

SHAFT DEWATERING STUDIES

Beginning in November 2013, the shaft excavation advanced into an andesite sill and below static groundwater elevation where inflow became significant. A grouting program was implemented to mitigate inflow and was only partially effective, groundwater continued to enter the shaft through bolt holes that penetrated the grout envelope and intersected fractures in the andesite. An initial dewatering well (DW-1, Figure 1) was advanced to a depth of 457 m with screen from 256 m to 457 m bgs. Three sets of nested vibrating wire piezometers were also installed at that time (Figure 1). An aquifer pumping test was performed on DW-1 at a rate of 28.4 liters per second (lps), the maximum achievable rate with the installed rental pump. The achieved drawdown in the pumping well was 76 m and 6 m was observed in VWP-01S at a distance of 130 m. The hydraulic conductivity (*K*) was determined to be between 0.6 and 3.3 m/day, more permeable than mean site values. The storativity was estimated to be 1.2-percent. The time-drawdown data was indicative of a modest negative boundary condition, attributed to the perceived displacement of the Flat Fault between DW-1 and the shaft, P-2 and P3 piezometers by the Shaft Fault (Figure 2 and Figure 3). The test responses varied significantly with depth, with the greatest response in P3 445 m piezometer in the Flat Fault, suggesting the Flat Fault was yielding the most of the water to the well.

Significant available drawdown remained during the DW-1 pumping test (approximately 215 m). However, step-testing in April 2014 indicated that higher rates could not be sustained. As a result, initial DW-1 operations began pumping rates between 25.2 lps and 27.4 lps. Since that time, the operational pumping rate of DW-1 has steadily declined, likely the result of compartmentalization of the Flat Fault (Figure 4). Shaft inflow rates have also steadily declined as the andesite has dewatered, the shaft has advanced beyond the andesite, a new substantially more effective grouting program was implemented in late January 2014 and DW-1 began operating (Figure 4).

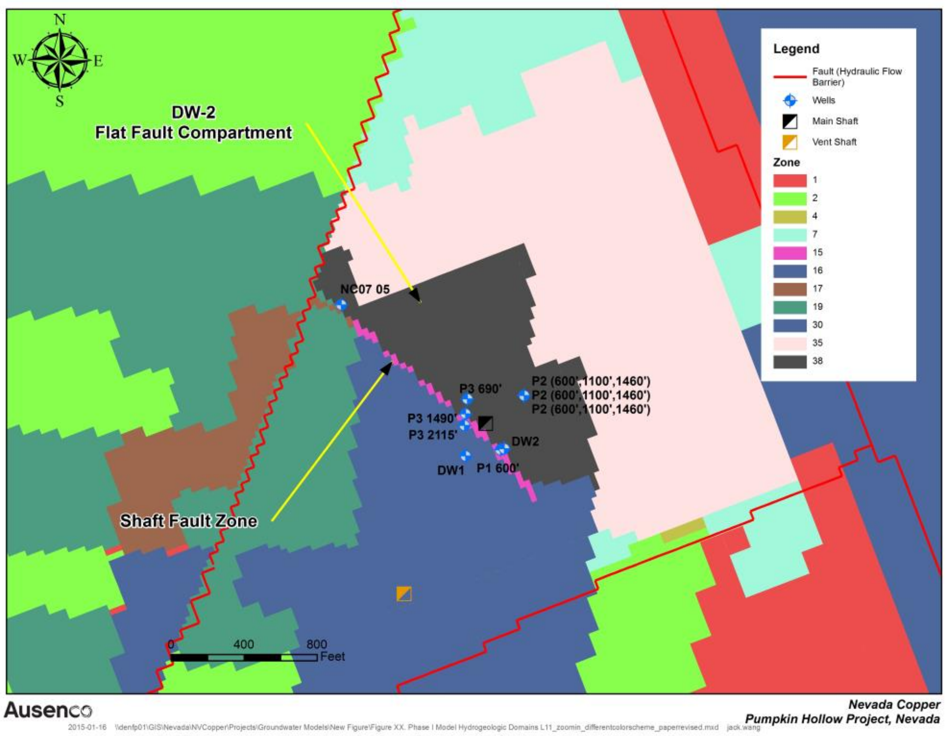

Figure 3 Geometry of the Flat Fault and Shaft Fault

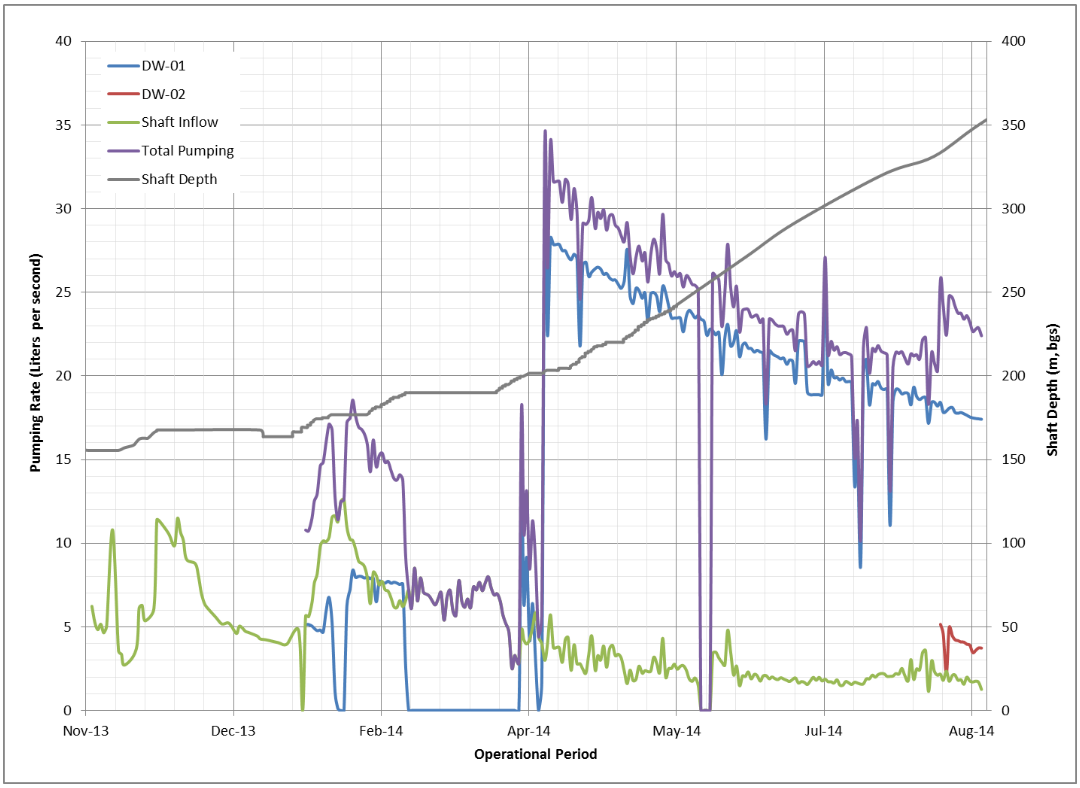

Figure 4 Operational Pumping Rates

A packer testing program and heat pulse flow meter testing were completed in geotechnical coreholes near a proposed vent shaft (Figure 1) to test the permeability of the deeper Mesozoic bedrock. Packer testing resulted in moderate *K* estimates for Mesozoic bedrock, between 2.0 x 10^{-4} m/day (746 - 759 ft bgs) and 4.9 x 10^{-1} m/day (609 – 624 m bgs) and heat pulse flow meter results yielded between 8.5 x10^{-3} m/day and 2.2 x10^{-1} m/day.

To further minimize groundwater inflow into the shaft, reduce pressure heads and reduce the need for costly grouting operations an additional dewatering well (DW-2; Figure 1) was installed upgradient of the shaft. DW-2 was completed to a depth of 632 m with screen between 198 m and 223 m bgs and 382 m bgs and 632 m bgs. DW-2 was commissioned August 16, 2014 pumping between 3.8 lps and 6.3 lps, much lower rates than what DW-1 (approximately 18 lps versus 4 lps) and numerical modeling suggested for DW-02.

Figure 5 presents the water level responses in vibrating wire piezometers at P3, including one in the Flat Fault (P3M 454 m), from the pumping of DW-1 and DW-2. Responses indicate the pumping of DW-1 in April impacted water levels in both the andesite and Flat Fault. It can also be seen that water levels within the Flat Fault were very sensitive to development and pumping at DW-2, despite the much lower pumping rate relative to DW-1. This is attributed to unforeseen geologic complexities, including compartmentalization of the Flat Fault by the Shaft Fault, the amount of clay gouge within the fault breccia and the discrete nature of the water bearing fractures in the Mesozoic rock beneath the fault gouge. These complexities result in a hydrogeological conceptual model (HCM) for the "DW-2 compartment" of the Flat Fault (Figure 3) that is significantly different than elsewhere on the property.

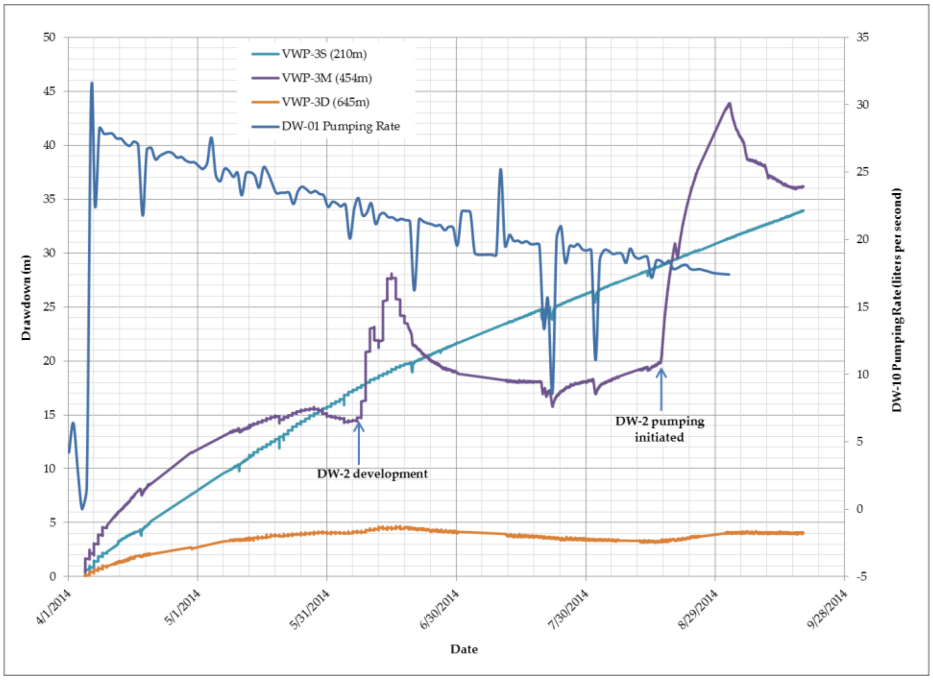

Figure 5 Measured drawdown and DW-1 pumping rates

Despite the lower pumping rate, considerable drawdowns occurred in the Flat Fault, Tertiary and Mesozoic bedrock. Accordingly, the seeps in the shaft walls dried up and inflows in the shaft appeared to decrease. Water levels within the Tertiary rhyolite tuff have also been significantly affected by pumping, with water levels in P2 (VWP at 335 m bgs) dropping by more than 90 m, since DW-2 began pumping.

GROUNDWATER FLOW MODELING

The objectives of the groundwater flow modeling were to develop a working tool to assist in improving our understanding of the hydrogeology in the area of the shaft and proposed East underground mine in order to predict the magnitude of groundwater inflow during shaft sinking, evaluate the effectiveness of the initial grouting program, evaluate pore pressures near the shaft and siting of dewatering wells and ultimately predict the groundwater inflow to the proposed East underground mine. An initial mine scale groundwater flow model (Hydro-Logic, 2014) was developed and calibrated using the 40-day DW-1 pumping test (initial model) and a second updated version of the model was calibrated using both the DW-1 (178 days) and DW-2 (15 days) transient calibration data sets and the updated hydrogeologic framework model (updated model) by Ausenco (2014). Both models also used the available shaft inflow data as part of the transient calibration. As a result of space limitations, some details of the models are not discussed here, instead the focus is on how incorporating the geometry and compartmentalization of the Flat Fault affected shaft inflow predictions and estimates of groundwater inflow.

Model Domain, Grid and Boundary Conditions

The Shaft Model domain (Figure 6) was extracted from the Regional Model (Tetra Tech, 2013) with the primary objective of having sufficient size to minimize boundary effects but also have an appropriately small size to allow for refinement in the area of interest near the shaft (7.5 m^2 cells). The grid was rotated to be consistent with the direction of groundwater flow in the area (Figure 6) and to align the axis with the primary fracture network orientation. General Head Boundary (GHB) conditions were developed for the Shaft Model based on the heads from the steady-state Regional Model results. Faults are generally interpreted to be hydraulic barriers and included using the hydraulic flow barriers (HFB), based on updated structural modeling in the project area. The model utilized Groundwater Vistas Version 6 (Environmental Simulations Inc., 2011) as a pre- and post-processor and groundwater flow was simulated using MODFLOW-USG (USGS, 2013).

In addition to incorporating well pumping rates and piezometer water level responses, transient calibrations included calibrating the conductance of HFB and the drain cells used to simulate faults and grouted sections of the shaft. The simulated shaft inflows (Figure 6) during the 40-day calibration period of DW-1 testing are on the order of 3.8 lps and are relatively consistent over the 40-day calibration period (Figure 4).

The calibrated *K* values for grouted shaft cells indicate that grouting activities through January 2014, were minimally effective as evidenced by high calibrated effective *K* (0.12 m/d). This is a reasonable assertion because the preferred pathway of water through the grout was through bolt holes and not through the grout matrix or remaining ungrouted fractures. Inflow data suggest that revised grouting methods have been significantly more effective with a calibrated effective *K* of 0.02 m/d or between level 2 and level 3 grouting as defined by Wilson and Dreese (2003).

A predictive version of each model was developed to simulate the dewatering of the shaft from the end of the respective calibration period May 5, 2014 (initial model) or September 30, 2014 (updated model) to the terminal depth of the shaft, 590 m bgs and 660 mbgs, for the two models respectively. The assumed *K* values for grouted sections of the shaft also evolved between model versions as a result of changes to the HCM and hydraulic properties. Principal differences include achieving level 3 ($K = 8 \times 10^{-3}$ m/d) grouting the Flat Fault in the updated model (versus level 2 or $K = 8 \times 10^{-2}$ m/d in the initial model) based on lower pressure and permeability expectations within the "DW-2 compartment". The assumed dewatering well pumping rates for the predictive model differ as well evolving from 18.9 lps for both DW-1 and DW-2 in the initial Mine Model to 17.3 lps and 3.1 lps in the updated Mine Model.

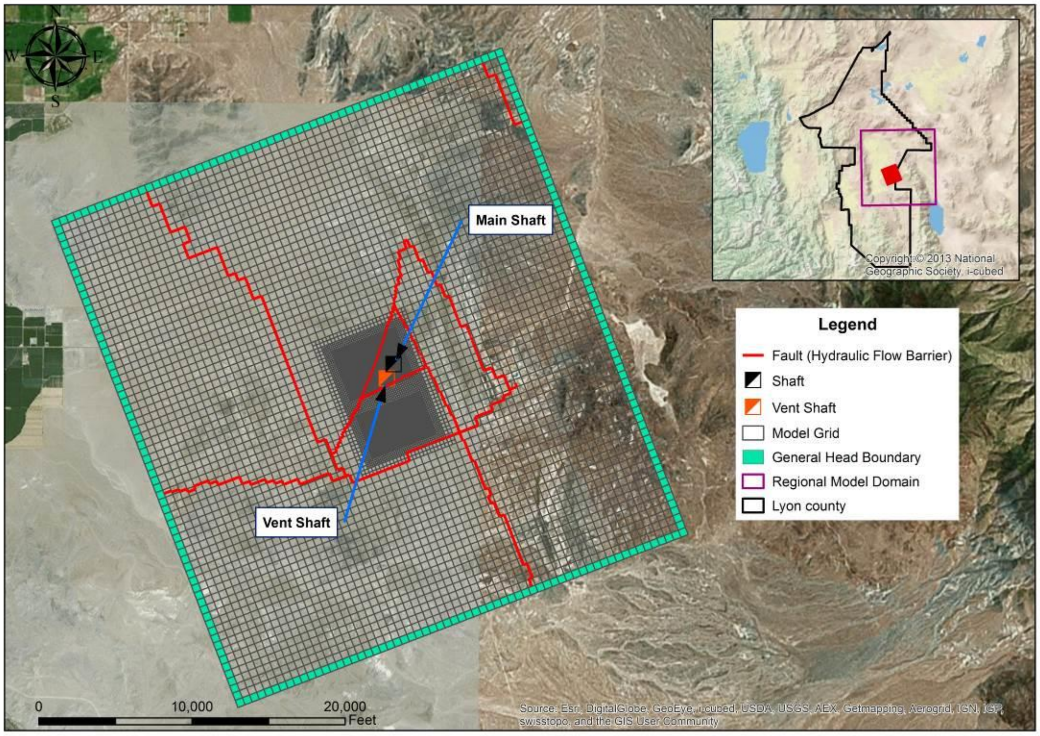

Figure 6 Shaft Model Grid, Boundary Conditions, Steady-State Groundwater Elevations

The calibrated *K* and storage parameters of the updated model were generally lower than in the initial model for both the Flat Fault and the Mesozoic bedrock. The calibrated Flat Fault response for the newly developed "DW-2 compartment" for the Flat Fault calibrated to a low specific storage, indicative of a discrete rock fracture response. Such values were required to mimic the hydraulic response at P3M to DW-2 pumping (Figure 5). This is consistent with an updated conceptual model of the Flat Fault in the "DW-2 compartment ", which suggests a discrete fracture confined by fault gouge, is able to rapidly transmit changes in pressure but dewaters rapidly due to limited transmissivity and storativity and the effects of compartmentalization. The expectation is that shaft probe holes may encounter high pressures but that the inflows in this zone will be short-lived.

Model Results

The model results were post-processed and examined as they related to the stated modeling objectives. Both models suggest that initial grouting performed in the shaft (up to February 2014) was relatively ineffective as the calibrated andesite *K* values (K_h = 0.6 m/d) are not reflective of overly permeable bedrock or values outside what would have been for such a rock type. Predicted inflows into the shaft have decreased in the updated model relative to the initial model (Figure 7), as the localized characterization (e.g. extent of clay gouge, lower *K* and storativity) and compartmentalized geometry of the Flat Fault have modified localized interpretations and calibrated hydraulic property values. Predicted mine inflow inflow through the Mesozoic rocks is lower than the initial model, as are the calibrated hydraulic properties. Available data suggest that, at most, periodic grouting will be required in higher yielding fracture zones of the Mesozoic bedrock.

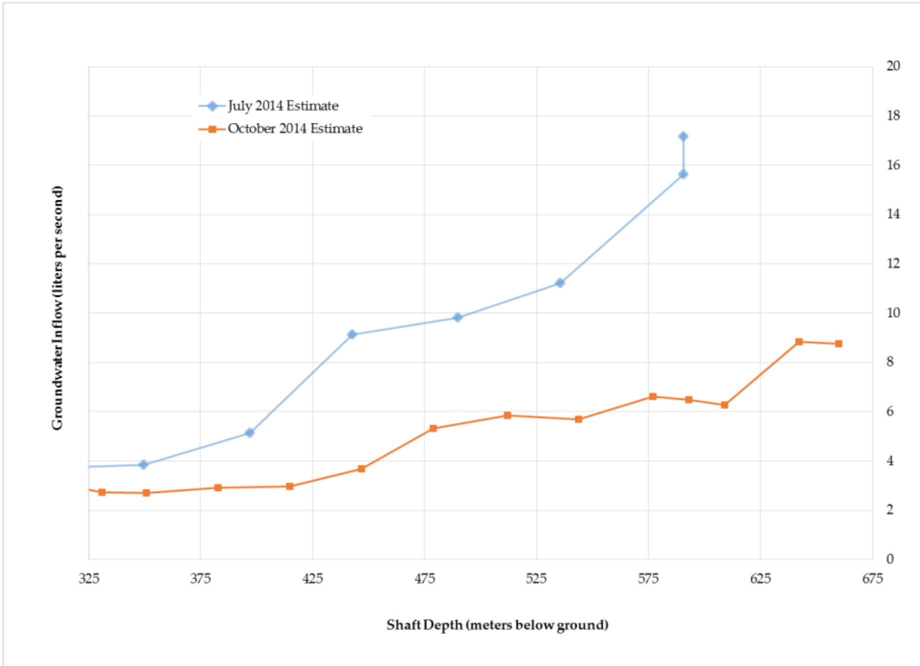

Figure 7 Predicted Inflow to the Shaft during Construction

The updated Mine Model was also used to predict groundwater inflow into the Phase I underground mine (first two years of mining). The base case estimated average monthly mine inflows for the first sixteen months are predicted to be 80 lps and for the last 12 months of operations the predicted monthly average is 120 lps. The Phase I mine simulation assumes that limited grouting will be completed and the groundwater inflow is governed by the native permeability of the surrounding bedrock.

CONCLUSIONS

The flow model results indicate that the calibrated *K* andesite sill (K_h=0.3 m/d) is greater than the range of values tested for Teritary Volcanic bedrock (2.0 x 10^{-4} m/d to 1.2 x 10^{-1} m/d) on the rest of the property, more than order of magnitude greater than the mean value (1.0 x 10^{-2} m/d) and two orders of magnitude greater than the median value of 1.8 x 10^{-3} m/d. This highlights the importance of not lumping hydraulic test results and HCMs in broad categories such as a 700 ft sequence of Tertiary volcanic rocks. The andesite sill in question was not being differentiated in the geologic model developed for quantifying ore reserves that was ultimately applied in geotechnical and hydrogeological assessments.

The inflow during shaft construction through the andesite was exacerbated by an initially ineffective grouting program. This assertion is supported by the decreasing shaft inflows and lower calibrated K values of the drains used to simulate grouted sections of the shaft. The revelation the DW-2 compartment of the Flat Fault and its differing hydraulic properties has led to a significantly different HCM than originally conceived. The depressurization of the DW-2 block of the Flat Fault is expected to result in lower groundwater inflows and pore pressures during shaft construction. As a result grouting will be less frequently required during shaft advancement.

These findings highlight the need for having a well-designed, site specific hydrogeologic characterization program in place prior to shaft sinking or other major development. However, on sites such as Pumpkin Hollow, where groundwater is compartmentalized and the hydrogeologic characteristics of the water bearing units are highly variable, changes in inflow can occur rapidly and shaft sinkers should be prepared to meet such challenges. As the project moves towards the underground mine development, the hydrogeology-geology team will work to improve our understanding of the compartmentalization at depth and the hydraulic properties of the Mesozoic bedrock and identify any potential zones of concern.

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