An Integrated Model for Mine Dewatering at the Bagdad Mine

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Abstract The ore deposit hydrogeology of large open pit porphyry copper mines in the southwestern U.S. typically involves large spatial variability in rock hydraulics. An integrated conceptual hydrogeologic model and validated predictive groundwater model are key to assessing dewatering and pit slope depressurization. In the case of the Bagdad mine, in Arizona, a 3D empirical model of the hydrogeology was developed using Petrel software. Three-dimensional hydrogeologic properties were exported to the MODFLOW-SURFACT groundwater modeling code providing a tool to target geologic zones for dewatering and pit slope depressurization. The resulting simulation accurately represents pit conditions and enhances mine planning.

Keywords Groundwater modeling, Petrel, Arizona, Groundwater Vistas, MODFLOW-SURFACT, dewatering, open-pit, mining, copper, MineSight, pit slope depressurization

Introduction

The ore deposit hydrogeology of large open pit porphyry copper mines in the southwestern U.S. typically involves large, spatial variability in rock mass hydraulics. The occurrence of groundwater flow and the distribution of groundwater pressure within the rock mass is influenced by many geologic factors including: structure, lithology, alteration, mining practices, and past and present mine dewatering efforts. Many of the Southwest mines require a program of pit slope depressurization to support geotechnical performance or a general dewatering program to maintain dry working conditions. An integrated conceptual hydrogeologic model and validated predictive groundwater model are key to decision making associated with dewatering and pit slope depressurization design and operation. In the case of the Bagdad mine, located in west-central Arizona, a sophisticated 3D empirical model of the mine hydrogeology was developed using the Petrel Seismic to Simulation software tool (Schlumberger 2011). Petrel allows for the storage, visualization, and interpretation of a wide variety of geo-scientific data types, the construction of geological models which include complex structures and the preparation of the input for and analyzing the output of numerical flow models.

A fully integrated analysis was completed in Petrel to examine relationships between rock mass properties, fault properties, and the distribution of observed flows and heads in pit slope horizontal drains, wells, and boreholes. The analysis allowed for improved understanding of the influence of lithology and structural sets/orientations on rock mass hydraulics. Three-dimensionally distributed hydrogeologic properties developed in Petrel were subsequently exported to the 3D MODFLOW-SURFACT (HydroGeoLogic, Inc. 2011) groundwater modeling code. The groundwater flow model was well calibrated to observed mine area groundwater levels and flows and has subsequently been used as a tool to target prospective geologic zones areas for dewatering production pumping and to guide the strategy for horizontal drain drilling in the less conductive slope sectors.

This paper describes the hydrogeology of the Bagdad mine and the process of constructing the Petrel and groundwater flow models to support the mine dewatering and pit slope depressurization program. The evaluation is relevant to any large open pit mine operation and represents an advancement in mine hydrogeology by integrating hydrogeologic information in the empirical model and accurately translating this into the conceptual hydrogeologic model. The result is a simulation that more accurately represents the pit conditions and enhances mine planning.

Site overview

The Bagdad mine, owned and operated by Freeport-McMoRan Copper & Gold; Inc., is a porphyry copper deposit containing both sulfide and oxide mineralization. Bagdad area covers approximately 38 mi^2 (98 km^2) and lies within a mountainous region located 100 mi (160 km) northwest of Phoenix, Arizona. The Bagdad mine consists of open pit mining of copper and molybdenum. The ore processing facilities include a mill/concentrator, several heap leach facilities, and a solvent extraction and electrowinning (SX/EW) plant. The current proposed mine plan includes deepening of the open pit by 1,000 vertical ft (300 m), along with significant lateral expansion over the 40-year Life of Mine (LOM).

The regional geology of the Bagdad area was described in detail by Anderson (1955) and consists of a combination of lava mesas and mountains cut by the deep canyons of Boulder and Copper Creeks. Many of the rocks exposed are a metamorphosed Precambrian complex with associated igneous intrusions. Erosion and deposition formed widespread conglomerates capped by regional basalt flows, which create the flat mesas seen today. The largest regional scale faults trend north-south and include the Hawkeye Fault, which bisects the current Bagdad open pit. Regional groundwater occurs within the highly faulted and fractured bedrock. Groundwater flow is generally from the Santa Maria Mountains to the northeast to the lower reaches of the Big Sandy and Santa Maria Rivers to the southwest of the mine. Regional groundwater elevations were based on data from Arizona Department of Water Resources drilling logs (ADWR 2011).

Historical dewatering efforts prior to 2010 were fairly minimal, consisting of 1) dewatering well pumping from less than 10 wells, typically for water supply purposes, 2) drilling of over 400 horizontal drains to depressurize specific pit slopes, and 3) continual pit sump pumping to remove groundwater inflow to the pit. In 2011, two dewatering wells produced a total of 200 gpm (13 L/s), approximately 60 horizontal drains were being drilled annually and pit sump pumping averaged 800 gpm (50 L/s).

Pit Area Hydrogeology

The vast majority of the open pit area consists of Quartz Monzonite (QM) and Porphyritic Quartz Monzonite (PQM) intrusions, which contain most of the ore body. The Precambrian Alaskite Porphyry (AP) intrusion comprises the upper slope of the west pit slope. The Precambrian metamorphic complex (PCM) comprises the upper slope of the south, east and northeast pit slopes. The Precambrian Lawler Peak Granite (LPG) is not exposed in the pit area but exists extensively behind the north and northeast pit slopes. The Copper Creek and Sanders Mesas make up the north and east pit crest, respectively. The mesas are comprised of Gila Conglomerate (Gila), overlain by Sanders Basalt (SanBas). Waste rock surrounds the open pit in the form of construction fill and roads. Historic tailings, waste rock piles, and heap leach dumps have been deposited in historic drainages on the south wall pit crest. Several major northwest-southeast trending faults bisect the pit area, the most significant of which are the Crusher Fault, Hawkeye Fault, Post/Gizmo Fault, and East Fault.

Groundwater Head Distribution

Over twenty, multi-level grouted-in vibrating wire piezometers (VWPs) have been installed in the pit area since 2010. The VWPs target specific pit slopes, geologic units, and structures, greatly increasing the understanding of the 3D groundwater head distribution. Continuous monitoring of VWPs using dataloggers has provided verification of dewatering and depressurization activities.

Pit area groundwater heads range from 3,400 ft (1,036 m) amsl on the south pit crest to 2,000 ft (610 m) amsl in the pit bottom (approximately land surface). Heads in the east, west, and north sectors are relatively depressurized compared to the south and northeast sectors. The south pit slope has elevated pore pressures due to pit crest facility leakage, while the northeast sector groundwater is fed by the highly fractured and permeable LPG.

Several structures appear to impact groundwater flow in the pit area leading to compartmentalization. Saturated pit slopes can be seen behind the Crusher Fault in the southwest sector, indicating groundwater is backing up behind the fault. The Hawkeye Fault separates the pit bottom into two compartments where dewatering well pumping west of the fault has little impact to the east. The Post/Gizmo Fault has shown increased groundwater production along its axis and has become a target for dewatering infrastructure. The East Fault appears to back up groundwater flowing into the pit from the east which will cause concerns for eastward pit expansions.

Groundwater Production

Bedrock groundwater production in the pit area is highly variable, with measured rates ranging from 0 to over 500 gpm (32 L/s). Along with known dewatering well pumping rates, airlift production rates during drilling were collected for over 20 RC drill holes from 2010 to present. Historic drilling records and logs were examined and groundwater production data was collected. Additionally, drain flow data was available for over 400 horizontal drains drilled within the pit from 2003 to present.

An initial assessment indicated that groundwater production was strongly tied to geologic units, with structural and sector-based influences. The QM, located on the south pit slope, tends to produce little or no groundwater, likely due to long-term alteration of the rock from pit crest facility leakage. PCM rocks tend to produce little groundwater except for along major structures such as the Post/Gizmo Fault. The AP, PQM, and QM located in the pit bottom and north wall tend to be moderately productive (25 to 100 gpm, or 1.5 to 6.5 L/s). The LPG, behind the northeast and north pit slopes, has produced over 500 gpm (32 L/s) in dewatering wells and appears to be pervasively productive.

Horizontal drain flow data shows that drains drilled into the east and west walls tend to be more productive than those drilled into the north and south walls, likely due to east-west drain orientations cross-cutting the northwest-southeast trending structures and fabric.

Hydraulic Testing and Parameters

Hydraulic testing has been performed since 2010 in the form of RC drill hole airlift/injection tests and dewatering well pumping tests. Hydraulic conductivity values are approximately proportional to groundwater production data. Measurements in PCM and south wall QM show bulk conductivities of $1 \cdot 10^{-6}$ to $1 \cdot 10^{-5}$ cm/s. AP and QM in the pit bottom/north wall show bulk conductivities of $1 \cdot 10^{-5}$ to $1 \cdot 10^{-4}$ cm/s. LPG and PQM in the north and northeast sectors show bulk conductivities of $1 \cdot 10^{-4}$ to $1 \cdot 10^{-3}$ cm/s. Storage parameters have been measured in a few locations from piezometer responses to dewatering well pumping tests. Measured storage values range from 0.0002 in the pit bottom QM to 0.003 in the LPG.

Petrel Model Development

A 3D Petrel model was developed to assemble all of the geologic and hydrogeologic datasets into one model format with the ultimate aim of creating a conceptual model/flow model grid. Petrel has numerous tools for 3D data visualization, spatial analysis and flow model grid creation.

The mine has developed a 3D resource geologic block model, using the MineSight software tool (Mintec 2011), based on considerable mineral exploration drilling. The block model represents the geology as 50 ft cubes within the mine area. The centers from each block were exported from MineSight and imported into Petrel as an exact copy of the MineSight model grid (Fig. 1). Topographic surfaces representing the current and pre-mine land surface were imported into Petrel as 3D lines and interpolated to continuous surfaces. Surface expressions and measured dips for major pit area structures were obtained from the mine and interpreted into 3D faults in Petrel.

Hydrogeologic datasets were imported into the Petrel model, including: surface collars and drilling paths for all dewatering wells, piezometers and RC holes containing hydrogeologic data; depth-specific well logs were imported along well paths, including RC airlift production with depth and interpreted hydraulic conductivity profiles; and water levels from multi-level grouted-in VWPs. In addition, collar locations and drilling paths for all horizontal drains were loaded into Petrel along with their measured flow rate.

Petrel Analysis

Petrel was used to perform analysis and interpretation on the geologic and hydrogeologic data to ultimately support the conceptual model and groundwater flow model. Analysis was done both qualitatively, through visualization of datasets, and quantitatively, through data statistics.

3D visualization of datasets is a key part of understanding the complex hydrogeology of a fracture based groundwater flow system. Petrel was used in conjunction with the resource block model and fault network to interpolate the hydrogeologic data. Analyses of hydrogeological features that could not be explained clearly due to the lack of historic data were evaluated by bringing together various data sources in Petrel. For example, little was known of an existing dewatering well with high groundwater production in the northeast sector of the pit. The path of the well was loaded into the Petrel model and overlaid with the resource block model, showing that the bottom of the well was in the LPG, which was hypothesized as the source of the production and later confirmed with additional drilling. Additionally, Petrel was a key tool in defining a low conductivity area on the southern pit wall, a major component of the conceptual model. Hydraulic conductivity, water produc-

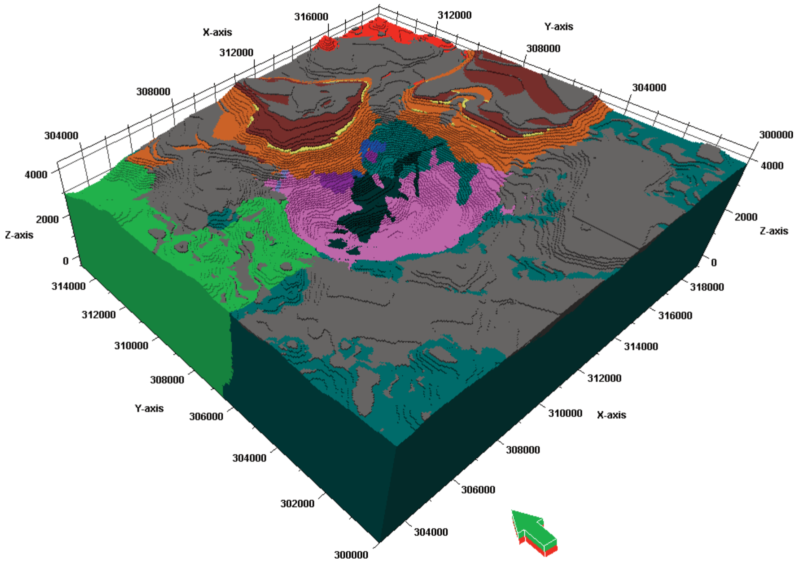

***Fig. 1**. Resource geologic block model imported into Petrel*

tion, multi-level VWP and drain data were loaded into Petrel and visualized to define a 3D volume of apparent low conductivity, low water production, and high pore pressure rock.

Extensive analysis was performed on the historic horizontal drain flow dataset, consisting of loading the drain paths and measured drain flow into Petrel, merging the drain flow data with lithologic and fault compartment properties, and performing general statistics on the results. Drain flow magnitudes were upscaled into the resource block model grid and output with geology and fault compartment codes. The analysis indicated that compartment between the Crusher and Hawkeye Fault was not sensitive to drain drilling and produced very little drain flow. It also showed that drains that cross key faults, such as the Hawkeye Fault on the north wall and the Crusher Fault on the west wall, tend to produce more groundwater. This analysis gave key spatial information on pit slope hydrogeology which helped guide future depressurization programs and supported conceptual model development.

Groundwater Flow Model Development

The inputs for a 3D numerical groundwater flow model were constructed in Petrel. The groundwater flow modeling code selected was MODFLOW-SURFACT for its increased performance in low hydraulic conductivity simulations. Groundwater Vistas v6 (Environmental Simulations, Inc., 2011) was used as the MODFLOW-SURFACT interface.

The total model area is approximately 168 mi^2 (435 km^2), with active cells comprising approximately 114 mi^2 (373 km^2). Model domain boundaries were placed at assumed hydrogeologic boundaries located away from the mine area. A tartan flow model grid was developed in the Petrel model, separate from the block model grid, consisting of 111 rows and 101 columns, rotated 37° to align with the primary northeast to southwest flow direction and predominant pit area structures and refined around the LOM pit (Fig. 2). Model layering was developed in Petrel as horizontal layers throughout the model domain, refined in the section covered by the mine block model. Boundary conditions were placed within the model domain, including drain boundaries to represent creeks and major washes, drain boundaries representing the surface of the open pit, and aerial recharge boundaries to represent bedrock groundwater recharge.

Cells within the active model area were grouped together based on geologic unit with the initial assumption that hydrogeologic properties are similar within a geologic unit. The resource geologic block model was upscaled into the flow model grid but only existed in the immediate mine area. USGS surface geology and geologic cross sections (Anderson 1955) were imported into the Petrel

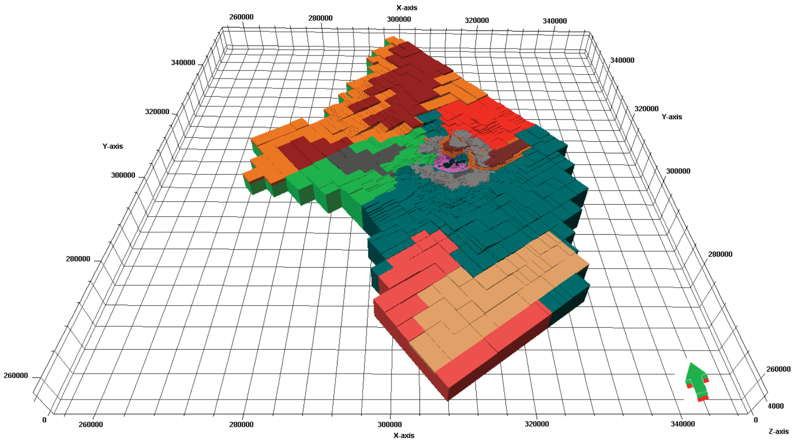

***Fig. 2**. Groundwater flow model grid*

model to guide the cell property population outside of the resource block model area. The focus of the model was the mine area so the regional geology was simplified into basalts, sedimentary (predominantly conglomerates) and intrusives.

Groundwater Flow Model Calibration

Calibration of the groundwater flow model was carried out in two phases. The first phase was a steady-state calibration to mid-2011 hydrogeologic conditions. The second phase consisted of transient calibration to dewatering well pumping records and piezometer responses over a six month period.

The steady-state calibration was achieved through the trial-and-error approach using hydraulic conductivity ranges defined by the conceptual model. The calibration was fine-tuned through the use of automatic calibration software. During steady-state calibration, several modifications to the hydrogeologic conceptual model were needed: 1) An "overbreak" zone was applied to the uppermost active model cell in the open pit area representing increased hydraulic conductivity due to blasting, 2) pit slope depressurization due to historic horizontal drain drilling was accounted for by applying increased hydraulic conductivities to those model cells intersecting drains in the Petrel model, and 3) the QM unit, compromising the majority of the pit, was divided into two distinct HGU's based on reduced hydraulic conductivity from long-term rock alteration on slopes below pit crest mine facilities.

The overall steady-state calibration resulted in a scaled RMS below 4 % and calibrated values of HGU hydraulic parameters were within ranges of the hydrogeologic conceptual model. Simulated flows in creeks within and at the edges of the model domain ranged from 100 to 500 gpm (6 to 31.5 L/s), which are reasonable given the climate and riparian ET rates for the area. Simulated groundwater inflow closely matched the open pit water balance and pit pumping data.

A transient calibration was carried out consisting of simulating pumping records from two pit-dewatering wells and matching measured piezometer responses to those wells. The correspondence between simulated and observed heads was improved by adjusting the storage values for all HGUs. Despite unknown or coarse pumping records, a reasonable transient calibration was obtained. Simulated pressure heads were exported from the groundwater flow model following the transient calibration and displayed on geotechnical cross sections for each pit sector in order to represent current groundwater conditions.

Groundwater Flow Model Predictions

The calibrated groundwater flow model was used to evaluate groundwater levels and pit slope pore pressures through LOM. Future mine plans were loaded into Petrel in order to construct the input files of pit surface drains and "overbreak" zone properties. Short-term mine plans were more detailed (quarterly to yearly stress periods) and long-term mine plans were more coarse (three to nine year stress periods), allowing for detailed analysis of near future depressurization strategy and LOM bulk dewatering strategy. All stress periods were combined into a single model using the Time-Variant Material Property Package (TMP1) of MODFLOW-SURFACT v4.0 to simulate the increase of hydraulic conductivity of the "overbreak" zone as the pit face advances through time.

A "Do Nothing" predictive model was run through LOM to simulate the development of the open pit with no active dewatering or depressurization measures (Fig. 3). The simulation results were provided to the geotechnical consultant and used as input to LOM pit slope stability models. The purpose of the "Do-Nothing" simulation was twofold: 1) provide a benchmark with which to compare active depressurization and dewatering simulations and 2) guide long-term dewatering strategy based on geotechnical slope stability results.

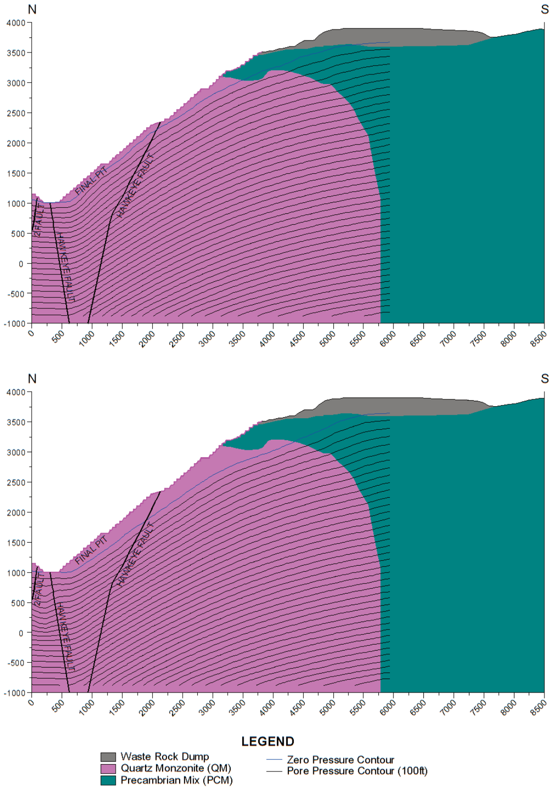

***Fig. 3**. Simulated LOM "Do-Nothing" (top) and Active Depressurization (bottom) results*

Active dewatering simulations were run through LOM based on the results of the "Do-Nothing" simulations and practical knowledge of the site hydrogeology. Dewatering wells and horizontal drains were simulated through LOM for lithologic units and pit slopes requiring active depressurization (Fig. 3). The results from the active dewatering simulations were fed back into the geotechnical slope stability models in an iterative process until an optimized dewatering and depressurization plan was achieved.

Summary

An integrated conceptual hydrogeologic model and validated predictive groundwater model were developed for the Bagdad open pit mine. The mine resource block model was integrated with hydrogeologic datasets in Petrel to develop a hydrogeologic conceptual model, which was exported to a 3D groundwater flow model grid. The flow model was calibrated to pit area flows and heads and subsequently used to predict pit slope pore pressures for future mine plans. Predictive pit slope pore pressures were fed into geotechnical pit slope stability models allowing the LOM dewatering strategy to be optimized.

Petrel Seismic to Simulation software was a key tool for data visualization, spatial hydrogeologic analysis, conceptual model and groundwater flow model development. Petrel is a three-dimensional interpretive modeling environment ideally suited for conceptual model construction and the preparation of inputs for groundwater flow models. Petrel is a standard tool for the oil and gas industry, where it is used for reservoir characterization and engineering.

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