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INSTRUMENTATION OF THE HOMESTAKE UNDERGROUND LABORATORY FOR DRAWDOWN MEASUREMENTS DURING DEWATERING

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ABSTRACT

The former Homestake gold mine at Lead, South Dakota, has been selected by the National Science Foundation as the proposed host site for the Deep Underground Science and Engineering Laboratory. The deep laboratory and associated research campus will be developed at approximately the 7700-ft level. Plans also include the development of the Sanford Underground Science and Engineering Laboratory at the 4850-ft level. After the mine's pumps were shut off in June, 2003, water levels rose to approximately the 4650-ft level by early 2008. Pumps in the 8150-ft deep mine were turned on again for dewatering in April, 2008. Instrumentation is being installed in the mine to measure water-level declines during pumping, for later analysis of permeability and related hydraulic properties of the formation. Pressure-sensitive transducers and data loggers will provide real-time information on water levels that will be available to interested parties. Quality of the water also will be monitored as it is pumped from the mine.

INTRODUCTION

Homestake Mine

The former Homestake Gold Mine in the Black Hills of South Dakota operated from 1876 to 2001. During that time, approximately 40 million oz of gold and 4 million oz of silver were produced. The mine supplied about 10% of the nation's total gold production to that date (Rahn and Roggenthen, 2002). The rock in the Homestake Mine is predominantly Precambrian phyllite. Mine workings in the gold deposit followed the Homestake Formation along four miles of plunge, penetrating through a volume of crust 1.7 x 1.9 x 3.1 miles, with more than 320 miles of workings. The deepest levels are about 8150 ft below the surface. The Homestake Formation is a complexly folded iron formation consisting of grunerite-siderite schist and chert. The underlying Poorman Formation is a well-banded sericite-biotite carbonate phyllite, and the overlying Ellison Formation consists of interbedded quartzite in sericite-biotite phyllite and schist (Campbell, 2006).

The rock sequence was folded several times and tilted toward the southeast during Precambrian time. Laramide tectonism raised the Black Hills to their current configuration and was accompanied by brittle fracturing, most likely creating the fractures presently observed in the mine. Later Tertiary alkalic volcanism (Shurr et al., 1996; DeWitt and Duke, 1996) intruded into the folded and fractured rock and is considered at least one of the proposed gold mineralization events (Paterson, 1996).

The Homestake site was selected as the Deep Underground Science and Engineering Laboratory in part because of its geologic and structural complexity and because such a large volume of crust is accessible for scientific and engineering experiments. Development of the site will occur in two phases. Phase 1 is the establishment of the Sanford Underground Science and Engineering Laboratory at the 4850-ft level, constructed with Federal, State, and private funds. Phase 2 involves construction of the DUSEL at the 7700-ft level and will be funded by Federal grants. It is anticipated Phase 2 will begin in 2010 or 2011. The South Dakota Science and Technology Authority (SDSTA) will administer the site.

Water Levels in the Homestake Mine

After mining ceased, pumps in the mine were shut off on June 10, 2003. Sensors were installed every 600-ft depth and have provided the crude data used to determine water rise over time (Figure 1). Post-closure flooding has resulted in rising water levels that reached the 4600-ft level in early 2008. Current inflow of water to the underground workings has been estimated at 750 gal/min. Figure 1 shows that the rise has not followed an exponential decay curve, presumably because of volume differences of mine openings at various depths, and permeability variations from fracturing at different locations. Initial calculations, based on the rate of inflow to the mine, the area of mine openings, and other factors, indicate that the bulk permeability of the fractured Precambrian rock is about 10^{-6} to 10^{-7} cm/sec (Davis et al., 2008).

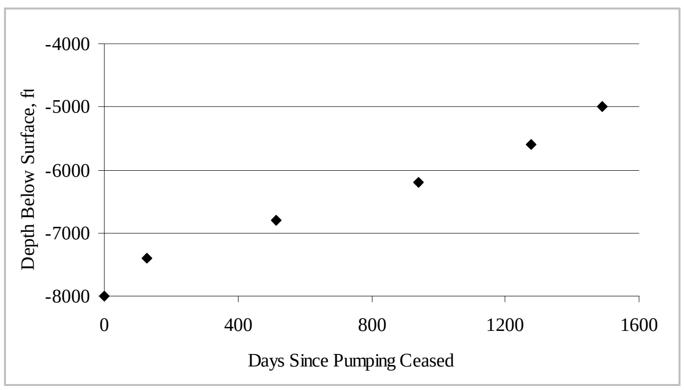

Figure 1. Water-level rise vs. time in the Homestake Mine. Day 0 is June 17, 2003, when water reached the 8000-ft level. Pumps had been shut off on June 10, 2003. Sensors were installed at every 600-ft level. Rising water reached the 5000-ft level in July of 2007.

Water enters the mine from the surface through drainage in shafts, airways, and the open pit. Ground-water flow occurs also through the fractured Precambrian aquifer. Approximately 2/3 of the inflow is above the 5300-ft level. Before mine closure, the largest single ground-water flow into the mine was 110 gal/min at the 8000-ft level. The mine workings dictate that flooding is occurring on two levels, an initial filling of the large voids represented by the shafts and drifts, and a secondary and longer-term infiltration into the fracture system. The water level in the bulk rock away from mine workings is unknown. Subsequent to pumping, as the water level is reduced, drainage is expected to follow the same pattern, first and fastest from the shafts and drifts, and a secondary and longer-term drainage from the fracture system. Thus, the water-level throughout the extent of mine workings during the reduction will not be linear.

The 600-ft sensor spacing currently in place is not sufficient to capture the quality of date required for both a hydrologic assessment of the aquifer system and rock mechanics studies that will occur in the mine. The required data with a higher spatial resolution can be collected through instrumentation of the mine with pressure-sensitive transducers located in available shafts that are connected to a wireless data transmission system.

EXPERIMENTS

Had the mine been instrumented properly when pumps were turned off in 2003, a huge piezometer test of historic proportions could have been monitored as the water level rose. It is crucial that a second opportunity not be lost when the water level in the mine is reduced. The planned dewatering of the Homestake Mine can perform as a giant pumping test if the temporal and spatial trends in the falling water table are accurately monitored. This is an unprecedented window of opportunity into the subsurface for hydrological studies which would be lost shortly if instruments were not emplaced to monitor falling water levels.

Experimentation will proceed on two fronts, hydrologic and climatic. The hydrology experiment will focus on collecting the falling water level using transducers that will be lowered into the water column from four of the five available access points from the 4850-ft level. These are the No. 6 shaft, either the No. 3 shaft which extends to the 5000-ft level or the service shaft which extends to the 6800-ft level (service shaft may not be accessible), the No. 4 shaft which extends to the 7400-ft level, and the No. 5 air intake shaft which extends to the 6200-ft level (Figure 2). All of these locations will yield data from the first water level reduction to the 5300-ft level, originally planned for December, 2007, and then delayed because of above-average precipitation in early 2008. Based on analysis of these data, a second experiment to collect the final water reduction data that most likely will not occur until ~2010.

Microclimate measurements will be concurrent with the hydrology experiment. Climate stations underground will be located on the 400, 1200, 2400, 3600, and 4850-ft levels (or nearest accessible levels). An additional station will be located on the surface near the Ross Shaft headframe on South Dakota Science and Technology Authority property. A station will consist of a combination humidity and temperature sensor, a barometer, and a wet temperature sensor. At each underground level, two stations will be installed, one close to the shaft and one up to 1000 ft from the shaft. These sensors will be connected to a wireless data transmission system underground and transmitted to the surface either by a wireless system or utilizing the existing cable system in the shaft.

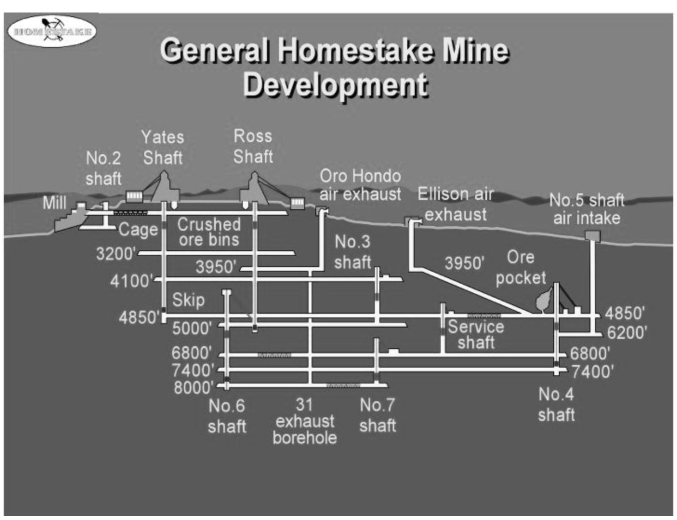

Figure 2. Cross section of part of the Homestake Mine, showing 4850-foot level and area of proposed Deep Underground Science and Engineering Laboratory.

As the water level in the mine is reduced, and the surface inflow is intercepted, climatic changes will occur. In addition, changes will occur as the mine goes from its current non-ventilated state into a fully ventilated sate. These climatic changes will be important to various experiments as the mine is prepared for the long-term science and engineering program. These early monitoring efforts will provide valuable information on the initial conditions of the research facility, while helping to establish a long-term monitoring effort.

DATA ANALYSIS

Dewatering

From the time that dewatering of the mine resumes in 2008, the rate of water-level decline will be monitored and the discharge rate will be recorded at the pumps and at the water interception stations. Both pumping rates and interception-rate records will be maintained while the water level is held at the 5300-ft level. The volume of pore space from mine openings will be factored out to separate this influence from the permeability of the rock at different levels, and the hydraulic conductivity at various levels will be calculated from the rate of water-level change. Information about the volume of mine openings at different levels is available from a three-dimensional mine model.

The goal of the data analysis will be characterization of the hydrologic properties of the Precambrian aquifer, including hydraulic conductivity (K), transmissivity (T), and storage coefficient(S). Analysis of inflow into mine workings or other openings in fractured Precambrian bedrock is complicated by several factors. Conventional analytical methods such as the Theis equation (Theis, 1935) typically assume a vertical well of infinitesimally small diameter. The Homestake Mine, because of its extensive vertical and horizontal workings at different levels, clearly does not meet this assumption. Later modifications of the Theis equation corrected for effects of wellbore storage and related applications (Jacob, 1947; Rorabaugh, 1953; Papadopulos and Cooper, 1967; Ramey, 1982; Dougherty and Babu, 1984; Moench, 1984; Daviau et al., 1985; Davis, 1987; Moench, 1988; Barker, 1988; Moench, 1997; Barlow and Moench, 1999; Kasenow, 2000; LeBorgne et al., 2006). These offer insight into adaptations that could be attempted; however, the Homestake Mine's horizontal extent of more than three miles indicates that analytical solutions developed for tunnel inflow are more appropriate.

The first widely accepted analysis of ground-water flow into tunnels was presented by Goodman et al. (1965). Freeze and Cherry (1979) provided an overview of relevant methods. For a tunnel that acts as a steady-state drain, the rate of ground-water inflow per unit length of tunnel can be estimated for a given hydraulic conductivity in a uniform medium. Alternatively, if the rate of inflow into the tunnel is known, a bulk hydraulic conductivity value can be calculated. Goodman et al. (1965) also presented a transient analysis in which specific yield (S_y), can be calculated for unconfined conditions, along with hydraulic conductivity. Application of their method is complicated by fractures but offers an initial means of estimating bulk values of K and S. Later work in the fields of tunneling and rock mechanics has been oriented toward prediction of inflow rates, using hydraulic conductivity values obtain from packer tests or other methods, especially in fractured areas. Wood (1975), Fitzpatrick et al. (1981), Atkinson and Mair (1983), Raymer (2001), Kolymbas and Wagner (2005), Lee et al. (2006), and Leis et al. (2007) presented more advanced methods for calculating tunnel inflows, including improved characterization of fractures.

In the analysis of water-level data during dewatering, analytical solutions will be tested for appropriateness of hydraulic conductivity determinations, including modifications for fracture flow and other factors. Results will be compared to those obtained from preliminary digital modeling of flow in a layered mine model, as well as flow-net analysis. The results, in turn, will provide new information about the hydrology of fluid flow deep within the earth and in determination of hydrologic properties of the local Precambrian aquifer, which are not currently understood. The data set for water levels from the transducers and other instruments in the experiment will be made available to other interested researchers.

Water quality also will be monitored as the mine is dewatered. An investigation of mine water quality before decommissioning was performed by Nelson (2003).

Microclimate

The goal of the microclimate analysis will be to characterize basic climatic patterns present within the mine prior, during, and post-dewatering. These will include temperature and humidity gradients with depth and distance along mine levels and changes in the mass of vapor as the mine is dewatered and becomes fully ventilated. As ventilation is again established in the mine, temperature fluctuations resulting from thermal and pressure gradients will most likely dominate observed patterns. Climatic variables collected at the microclimate stations will be added to ventilation data (air volume and pressure), obtained from the SDSTA, for analysis. Analytical techniques range from simple regression models (Simmons, 2002; Wang, 2003) to more sophisticated three-dimensional models.

USE OF RESULTS

Results from the hydrology and microclimate experiments will be used by the SDSTA and other researchers to design future scientific and engineering experiments at Homestake. The SDSTA will use both sets of results in the mine design plan. The climatic data will provide design engineers with an up-to-date picture of current environmental conditions underground and how these conditions are altered by increases in underground trips, ventilation, and reduction in the water level. The hydrologic properties of the rock will also become a focal set of data when excavation of new space is required.

A website will be established, hosted either by the Homestake DUSEL or South Dakota School of Mines and Technology, to post the data on a regular basis. As analysis efforts are initiated, the generated plots and analytical methods will be posted on the website. The raw data also will be preserved at the web site, for electronic availability to other researchers.

ACKNOWLEDGMENTS

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