

Underground Reconnaissance and Environmental Monitoring Related to Geologic CO₂ Sequestration Studies at the DUSEL Facility, Homestake Mine, South Dakota

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November 2009

Abstract

Underground field reconnaissance was carried out in the Deep Underground Science and Engineering Laboratory (DUSEL) to identify potential locations for the planned geologic carbon sequestration experimental facility known as DUSEL CO₂. In addition, instrumentation for continuous environmental monitoring of temperature, pressure, and relative humidity was installed at various locations within the Homestake mine. The motivation for this work is the need to locate and design the DUSEL CO₂ facility currently being planned to host CO₂ and water flow and reaction experiments in long column pressure vessels over large vertical length scales. Review of existing geologic data and reconnaissance underground revealed numerous potential locations for vertical experimental flow columns, with limitations of existing vertical boreholes arising from limited vertical extent, poor continuity between drifts, and small diameter. Results from environmental monitoring over 46 days reveal spatial and temporal variations related to ventilation, weather, and ongoing dewatering of the mine.

Introduction

As part of a long-standing effort to combine physics and geologic research in a deep underground laboratory, Kevin Lesko (NSD) and Joe Wang (ESD) developed a successful LDRD proposal (funded during FY07-FY09) entitled “Physics Detector and Sensor Technologies Applied to Geological and Geophysical Applications at DUSEL.” One aspect of this LDRD study was the evaluation of methods for “underground carbon remediation techniques,” more commonly known as geologic carbon sequestration. Work was proposed to evaluate the possibility of using the DUSEL facility to conduct *in situ* underground experiments to study the behavior of injected CO₂ in the subsurface, focusing on phase transition, migration, and dispersion. The initial phase of this work focused on investigating the locations of sand line boreholes within the Homestake mine (Wang, 2008).

In late 2008, a group of scientists at LBNL teamed up with colleagues at Princeton University to develop a proposal aimed at designing a facility for carrying out CO₂ flow experiments that will use long column pressure vessels for fluid containment rather than the natural rock in the former mine. The project team, currently supported by the National Science Foundation (as part of the S4 call for proposals for initial experimental designs at DUSEL), is developing the design, procurement, construction, and operational parameters for this facility, known as DUSEL CO₂, and evaluating the feasibility of a suite of initial experiments (Peters et al., 2009). The team will conduct outreach with the local community as well as with other scientists interested in developing experimental methods to improve understanding of flow, transport, and reactivity of CO₂ in the subsurface. This will be a unique facility capable of testing large-scale trapping and migration processes, the understanding of which is needed to establish large-scale geological sequestration of carbon dioxide as both safe and effective.

This report summarizes the work that was conducted in FY09 to support the objectives of the LDRD related to potential geologic carbon sequestration experiments at DUSEL. This consisted of a review of the existing literature on the Homestake mine, a site visit to

view potential locations for the proposed DUSEL CO₂ experimental facility, and the deployment of environmental monitoring sensors at three different levels within the mine to record temperature, relative humidity, and barometric pressure.

Homestake Mine and DUSEL

The Homestake mine is the site of the largest gold deposit in North America, yielding over \$1 billion in gold over its long history. The gold is associated with sulfide mineralization in the Homestake formation, an early Proterozoic banded iron formation (Caddey et al., 1991; Frei et al., 2009). This unit is associated with a series of metasedimentary and metavolcanic rocks that were deposited about 2.0 Ga. The oldest unit of this sequence is the Poorman Formation, a well-banded biotite phyllite (Ross member) and hornblende-biotite schist (Yates member). Overlying this unit is the Homestake Formation, consisting of a siderite-grunerite schist with interbedded chert. These rocks are capped by the Ellison Formation, consisting of interbedded quartzite and biotite schist.

These units underwent metamorphism associated with granitic intrusion at about 1.71 Ga (Frei et al., 2009). The rocks also underwent deformation during this orogenic event, resulting in the generation of tight isoclinal folds and shearing (Fig. 1); this deformation is coeval with gold mineralization at Homestake. This area was subsequently uplifted to form the Black Hills uplift at about 530 Ma. The area was the site of early Tertiary alkalic volcanism, and there are numerous trachytic dikes and sills that cut the early Proterozoic metamorphic sequence.

The Homestake deposit was discovered during the Black Hills gold rush of 1876. During 1965-1967, a physics neutrino detection facility (the Davis chamber) was constructed on the 4850' level of the mine to measure the flux of solar neutrinos above 0.814 MeV (Cleveland et al., 1998). Observations obtained from this facility showed that the neutrino flux was well below the solar model prediction; this pioneering work resulted in a Nobel Prize in Physics in 2002 for Dr. Ray Davis.

Gold mining operations ceased at Homestake in 2001, but there was continued interest amongst the scientific community to utilize this facility as an underground science laboratory. The state of South Dakota acquired the mine from the Barrick Gold Corporation for this use, and with the support of T. Denny Sanford, established the Sanford Underground Science and Engineering Laboratory. One of the key activities undertaken by South Dakota (through the South Dakota Science and Technology Authority) was to restart the pumps to reverse the flooding of the underground workings. After a competitive review and selection process, Homestake was selected in 2007 by the National Science Foundation as the site for a multipurpose deep underground and engineering laboratory (DUSEL). The science activities at DUSEL are being coordinated by Dr. Kevin Lesko of UC Berkeley/LBNL. Science teams are currently putting together preliminary design reports for the envisioned DUSEL facility.

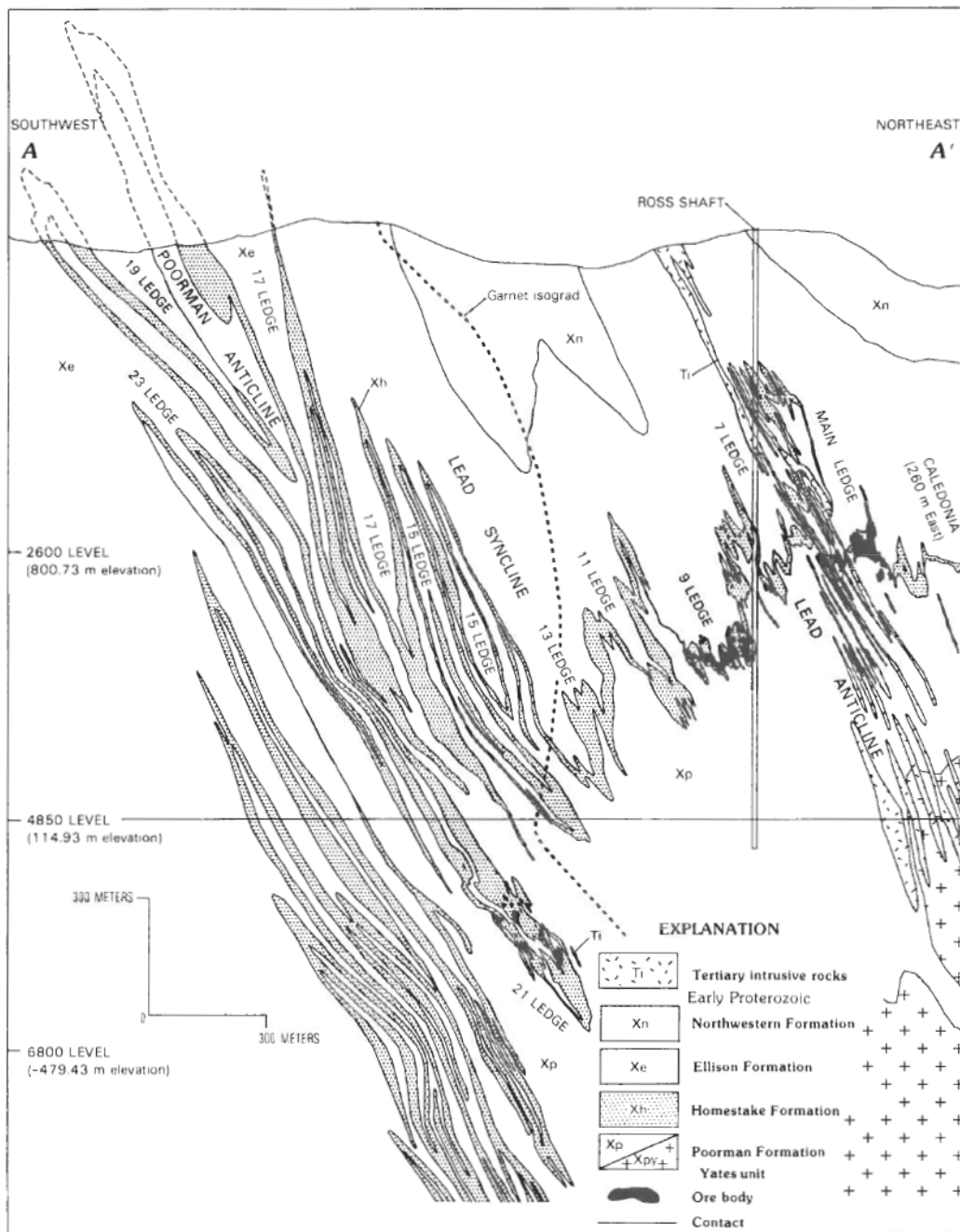


Fig. 1: Cross section through the 33 Stope, Main Reference Section, Homestake Mine. Note that the gold mineralization is intimately associated with the Homestake Formation. Figure taken from Caddey et al., 1991.

Concept for Underground CO₂ Experiments at DUSEL

The primary research objective of the proposed DUSEL CO₂ facility will be to understand the processes that control CO₂ trapping and migration, including unintended leakage. The experimental design will exploit the large vertical extent of existing borings and drifts at Homestake. The facility as currently envisioned would consist of a series of vertical flow columns (~400 m) schematically depicted in Fig. 2. The installed columns would contain the CO₂ and allow control of pressure and flow rate. The flow columns

can be filled with selected porous media such as alternating layers of sands and clay, as well as with cements to mimic plugged wells.

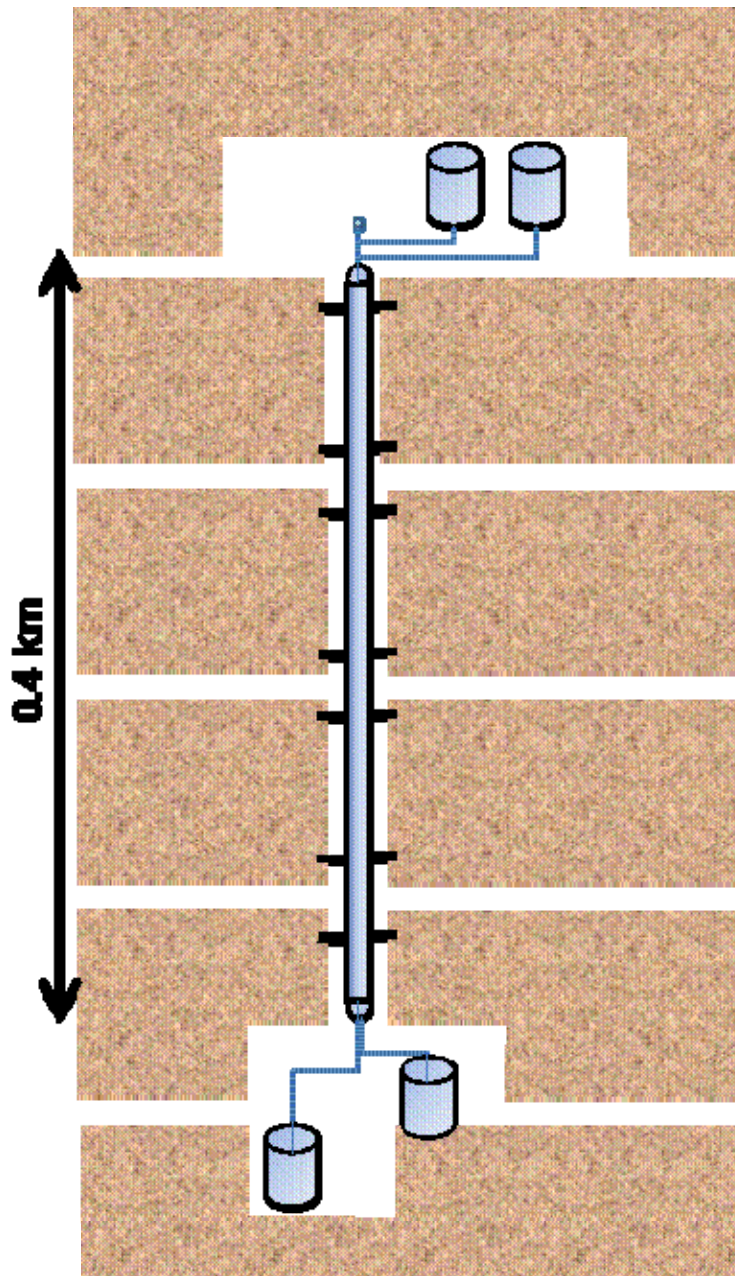


Fig. 2: Conceptual model for the DUSEL CO₂ facility. The column would cross intermediate drifts, which would allow for sampling of fluids at different depths. Fluid flow would be controlled by tanks and compressors located at the top and bottom of the flow column. In the current design, three separate columns would be installed in a single bored raise.

A preliminary experimental design package, consisting of potential location within the DUSEL facility, facility requirements, identified hazards, and initial estimates of project schedule, milestones, and costs, is currently being developed by the DUSEL CO₂ S4 team. The primary requirement for the DUSEL CO₂ facility is a continuous, long (~400

m), vertical boring (raise) of sufficient diameter to accommodate 1-3 long column pressure vessels that can be supported, monitored, and maintained within the boring (raise).

Prospective Locations for DUSEL CO2 Facility at Homestake

Joe Wang previously identified a number of potential locations that would utilize existing sand lines at the Homestake mine. During our visit to the mine in June 2009, we focused on looking at the types of vertical/near vertical borings that were present on the 1700' level. We observed several different types of borings: sand lines, power holes, drain holes, and air raises (Figs. 3-5). These features ranged in diameter from around 6-8 in (15-20 cm) for the sand lines, power holes, and drain holes to up to ~5 ft (1.5 m) for the air raise.



Fig. 3: Cased sand line on 1700' level near the #2 Air Raise.



Fig. 4: Uncased 6-in (15 cm) diameter drain hole near the #2 Air Raise on 1700' level.



Fig. 5: The #2 Air Raise on the 1700' level. This feature, about 5 ft (1.5 m) in diameter, extends upwards (perhaps as far as the 1100' level), and goes down to the 2000' level. It is partially obstructed with rubble below the standing water.

The larger diameter (~13 in / 33 cm) sand lines that Joe Wang had previously investigated are located near the Ross Shaft. However, these features are now designated as off-limits to experimental use for safety reasons, as they are reserved for fire suppression purposes within the mine (Tom Trancynger, pers. commun.).

Our assessment of vertical borings at DUSEL is that siting DUSEL CO₂ in existing boreholes is not feasible. Existing workings are either of limited vertical extent, filled with rubble and debris, or have diameters that are too small to house long column pressure vessels. This conclusion prompted discussion of the possibility of boring new holes explicitly for the purpose of the DUSEL CO₂ facility. This option would be more costly, but would allow for the holes to be tailored specifically for the project, thus permitting that the location, diameter, and length of the hole(s) could be specifically engineered for the project.

Environmental Monitoring

Previous Environmental Data for Homestake

There are several sources of data available for temperature measurements at the Homestake mine (Fig. 13). A Homestake Mining Company internal report (Homestake Mining Company, 1973) plots observed rock temperatures vs. depth for the principal shafts in the mine in 1973, with temperatures of 34 to 35°C for the 4850' level. A linear fit to the different plotted temperature measurements yields a thermal gradient of 21°C/km, resulting in a predicted temperature of 54.3°C at the 8000' level. Very similar thermal gradient values were reported by Roy et al. (1968) for the #4 shaft (23.4°C/km) and the Yates Shaft (19.0°C/km), with a calculated mean heat flow value of 1.9 $\mu\text{cal}/\text{cm}^2$ sec. A thesis by Chancellor (1981) examined temperatures recorded on the 8000' level of the Homestake mine. This study indicated large differences between drift temperatures and rock mass temperatures, with increasing temperatures observed with increasing distances into the rock from the drift. For example, the ventilated drift temperatures for a station at this level varied from 31.4 to 40°C (reflecting changes in ventilation of the area), a sensor located 1.4 m from the drift wall recorded temperatures from 42.5 to 49.0°C, and a sensor located 12.2 m from the drift wall recorded temperatures ranging from 55 to 71°C. Finite element analysis of temperature data obtained from temperature profile measurements on the 7000' level (Ashworth, 1983) also demonstrated how ventilation in the drifts resulted in cooling of the rock near the drift walls at depth.

Environmental Monitoring Stations

Environmental monitoring stations were deployed at the Homestake mine at the 800', 2000' and 4850' levels on June 10, 2009. Each station contained a barometric pressure monitor, two relative humidity sensors, and two temperature sensors, with one set of the relative humidity and temperature sensors deployed in the drift and the other set located in a borehole in the drift wall. The objectives of this monitoring study were:

- 1) To look at differences in temperature and relative humidity between the drift (which would be affected by ventilation) and within the rock mass,
- 2) To examine differences in temperature, relative humidity, and barometric pressure as a function of depth,
- 3) To look at temporal changes in environmental conditions,

- 4) To compare results with previous environmental records from the mine
- 5) To determine if the natural thermal gradient of the mine could be used to heat the proposed long column pressure vessels planned for DUSEL CO₂.

The three locations were chosen to span the potential depth range that the experimental system for the CO₂ flow columns might encounter at Homestake. Each monitoring station was equipped with a Campbell Scientific data logger (Model CR10X), a Vaisala pressure transmitter (Model PTB101B), and two Campbell Scientific temperature/relative humidity probes (Model CS500-L). The barometer has a range of 600 to 1060 mbars, with an accuracy of ± 0.5 mbar at 20°C. The temperature/relative humidity probe has a platinum resistance temperature detector, with a measurement range of -40 to +60°C and an accuracy of $\pm 0.6^\circ\text{C}$ over the temperature range of interest (10 to 40°C). The probe also has capacitive relative humidity chip with an accuracy of $\pm 3.0\%$ for values in the range of 10-90%, and $\pm 6.0\%$ for relative humidity values between 90-100%. The 800' and 4850' stations were powered using 12 V marine batteries, while the 2000' station utilized an available 110 V outlet. The openings of the boreholes used for the drift wall probes were sealed with insulating foam to reduce the effects of drift ventilation on these sensors.

The shallowest environmental monitoring location was sited on the 800' level (Figs. 6 & 7) near the junction of the drift that leads to the Oro Hondo shaft (~235 ft (72 m) from Ross shaft and ~15 ft (4.6 m) from the header to the Oro Hondo shaft). The external (in-drift) set of sensors was mounted on timbers along the right rib, and the internal sensors were positioned 55 cm inside a bore hole found near the top of the right rib.

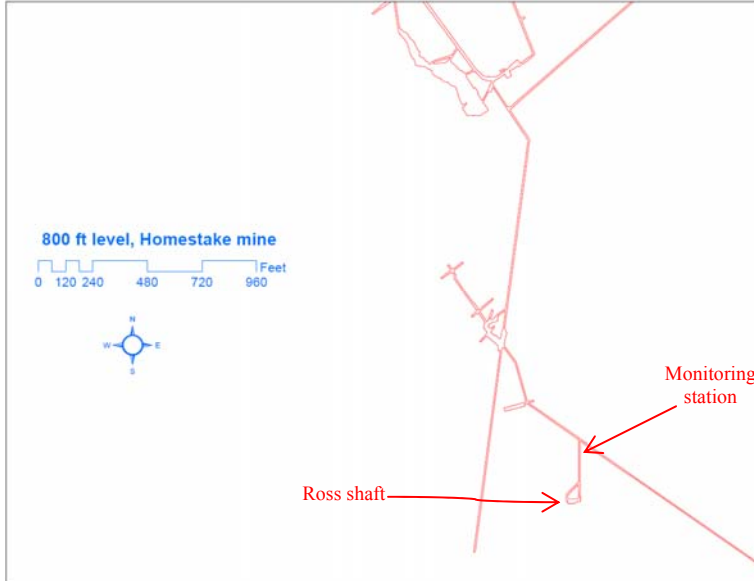


Fig. 6: Location of environmental monitoring station on 800' level.



Figure 7: Monitoring station on the 800' level.

The intermediate depth location was at the 2000' level in a side drift where the Roggenthen Far Site station is located (Figs. 8 & 9). The external (in-drift) set of sensors was deployed within the drift against an iron pipe near the top of the left rib, and the internal sensors were inserted 5.4 m into an inclined borehole near the base of the drift.

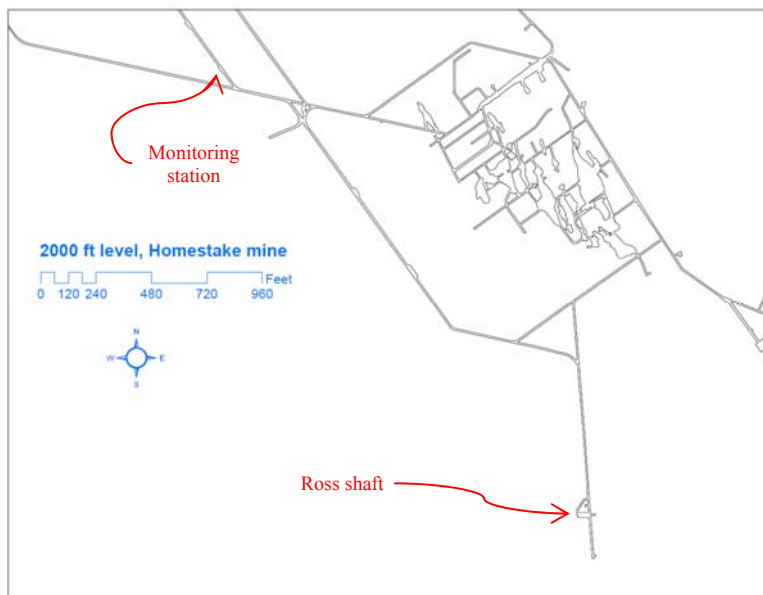


Fig. 8: Location of environmental monitoring station on 2000' level.



Fig. 9: Monitoring station on the 2000' level.

The deepest monitoring station was deployed on the 4850' level by a concrete pad located about 30 ft (9 m) down the crosscut to the #6 Winze (Figs. 10 & 11). The

external sensors were mounted on a rock bolt on the right rib, and the internal sensors were inserted to a depth of ~2.4 m in a newly drilled near-horizontal hole.

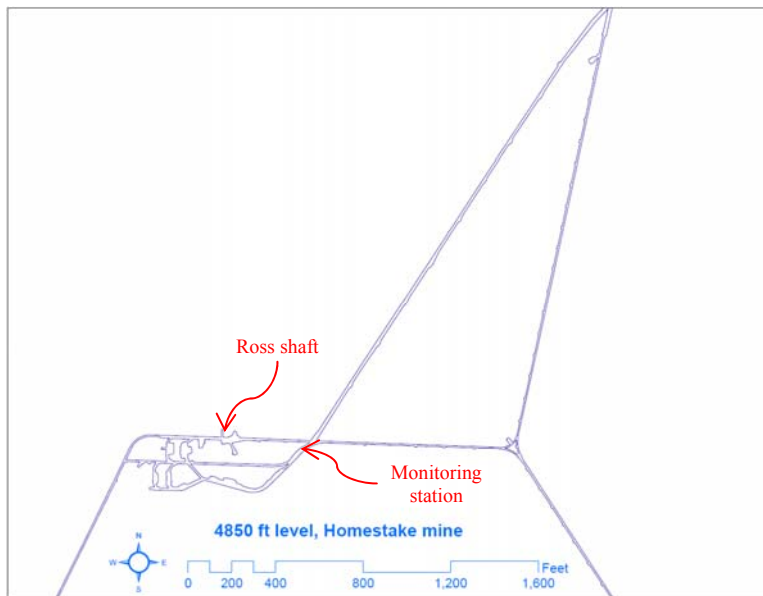


Fig. 10: Location of environmental monitoring station on 4850' level.



Fig. 11: Monitoring station on the 4850' level.

Results of Environmental Monitoring

Data were collected at each monitoring station between June 10, 2009 and July 27, 2009 at 15-minute intervals. The data were retrieved from storage modules attached to each data logger. Unfortunately, the system did not continue to collect data on the replacement storage modules after the initial data download, so the data are limited to this 46 day period. The results of the temperature, barometric pressure, and relative humidity measurements are summarized below.

Temperature

Temperature values vary systemically as a function of depth within the mine, with increasing temperatures observed with increasing depth (Figs. 12 & 13). Temperatures also are affected by whether the probe is located within the drift or mounted in a borehole within the rock mass, and also by the proximity of the station to the ventilation shaft.

For the 800' level, there are gradual but minor increases in temperature for both the drift and borehole probes, with more fluctuations observed in the drift environment. The drift temperatures are about 0.6°C higher than those observed in the isolated borehole. The final borehole temperature (12.1°C) is higher than the temperature reported by Homestake (1973) for the same level at the Yates shaft (9.9°C) and the extrapolated temperature for the #5 shaft (11.2°C).

At the 2000' level, there is very little difference observed between the drift and borehole temperatures, with the average drift temperature being only 0.3°C higher than the average borehole value. This site also exhibits the least amount of fluctuation in drift temperatures over the monitoring period. This is probably due to the remote location of the monitoring site in a side drift that is more than 2500 ft (760 m) away from the Ross shaft (Fig. 4), thus minimizing the impact that ventilation has on the drift temperatures. The reduced ventilation effects for this site are also supported by the high (> 98%) relative humidity values also observed at this site (Fig. 15). The final borehole (16.3°C) and in-drift (16.5°C) temperatures at this level are similar to the rock temperature indicated by the Yates shaft thermal gradient by Homestake (Fig. 13) for this level (16.8°C).

There is a much larger discrepancy between the in-drift and borehole temperatures observed for the 4850' level, with the drift temperatures averaging over 4°C cooler than the borehole probe values. There is a pronounced variability in the drift temperatures that is likely due to ventilation, as this site is located less than 500 ft (150 m) from the Ross shaft. This area is also a location where quite a bit of construction activity has been occurring, which would also result in changes in ventilation. The inferred effect of ventilation on decreasing the drift temperature is supported by the lower relative humidity values also seen at this location (Fig. 15). One trend that is different from the other sites is the systematic decrease in the borehole temperature observed at the site with time, from early values of ~28.6°C progressively decreasing to temperatures of ~27.1°C at the end of the monitoring period. This site had been submerged for an extended period of time after the mine ceased operations (the 4850' level was first cleared of water on May 13, 2009), so this decrease in temperature over time might reflect evaporative cooling

occurring within the rock mass as the water saturation level of the rock is reduced over time. The final borehole temperature (27.1°C) is quite a bit lower than the Homestake mine rock temperature values (Yates shaft $\approx 34.0^{\circ}\text{C}$ and #4 Shaft $\approx 35.0^{\circ}\text{C}$) reported for this level (Fig. 13), which would also support the hypothesis that the borehole values measured in 2009 do not represent stabilized, equilibrated values. The much lower thermal gradient suggested by the new rock data (12°C/km compared with the Homestake value of 21°C/km) may be in part an artifact of these unequilibrated values. Additional data are needed to resolve the discrepancy between these two sets of temperature results.

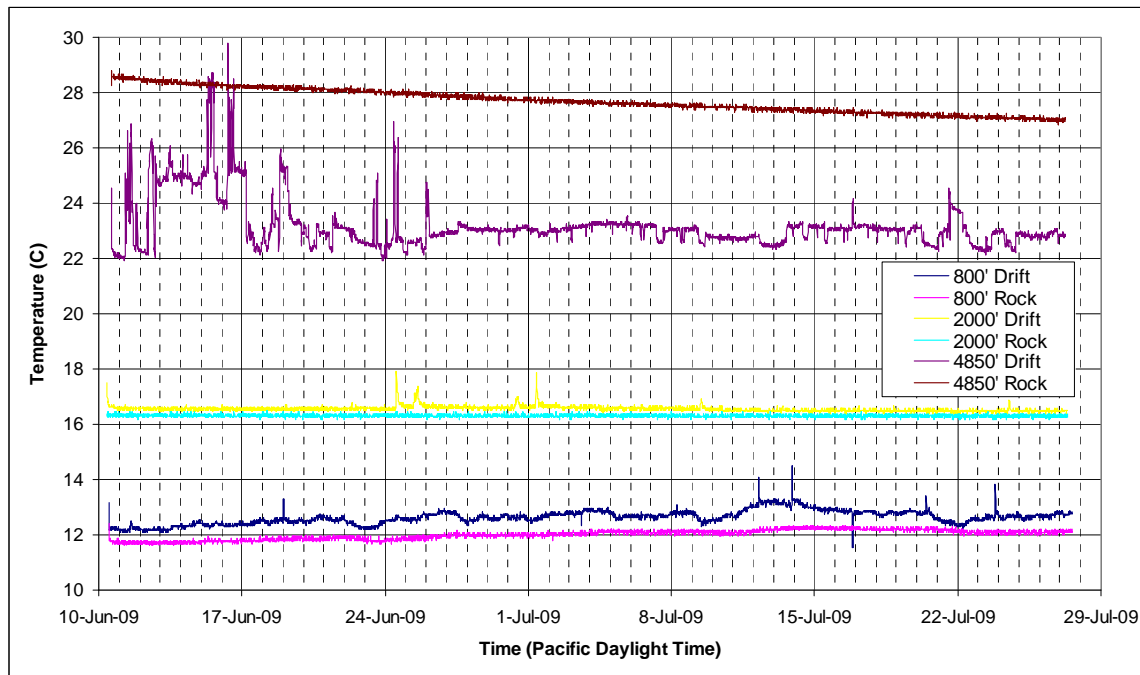


Fig. 12: Temperature variations for in-drift and borehole probes recorded at three depths within the Homestake mine.

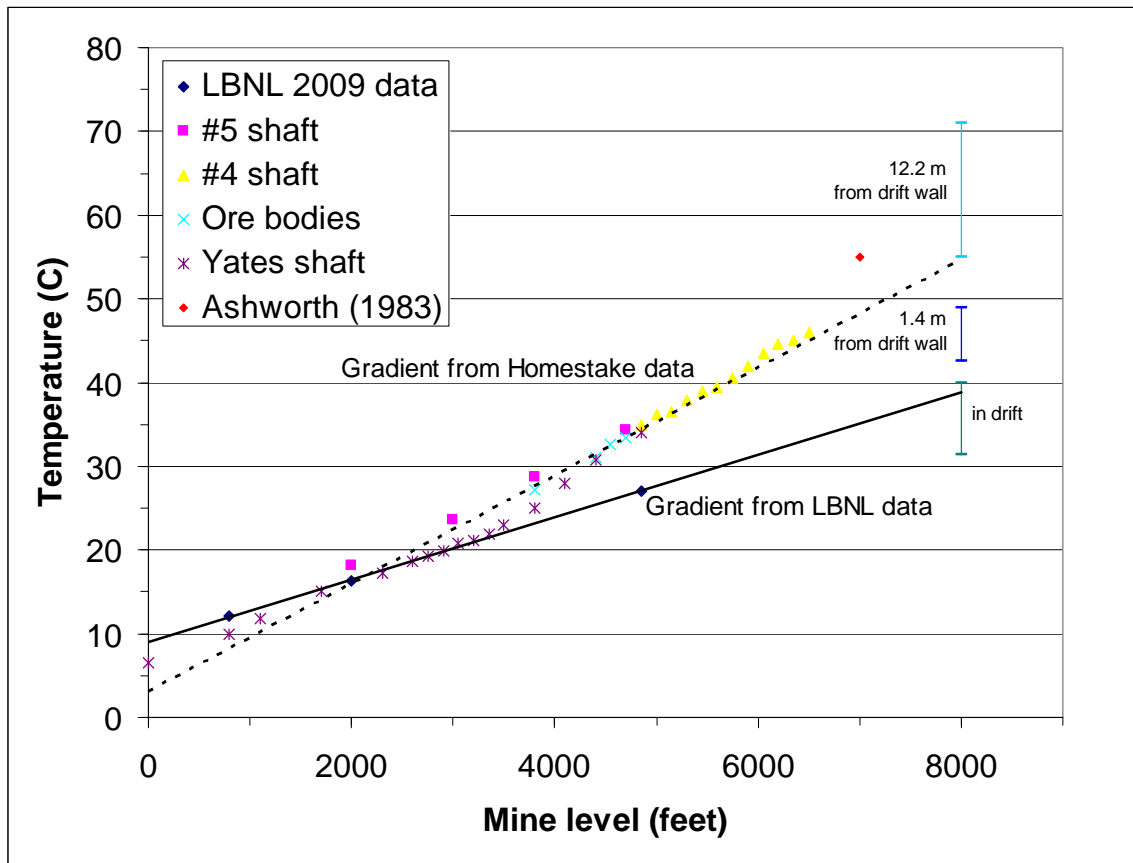


Fig. 13: Comparison of LBNL rock temperature data with that reported by the Homestake Mining Company (1973), Chancellor (1981), and Ashworth (1983). Note that the linear temperature gradient obtained from the LBNL data is much lower than that reported by Homestake using data obtained from the Yates, #4, and #5 shafts and ore bodies. The ranges of temperatures recorded by Chancellor at the 8000' level in the drift, at 1.4 m from the drift wall, and at 12.2 m from the drift wall are also noted. A “virgin” rock temperature of 55°C for the 7000' level was calculated by Ashworth (1983) based on measured values and finite element modeling.

Barometric Pressure

Systematic variations in barometric pressure are observed at all three stations (Fig. 14), with the highest pressures observed at the deepest level (4850' = 115 meters above sea level - masl), intermediate values at the 2000' level (984 masl), and the lowest pressures at the shallowest level (800' = 1350 masl). Pressure values for each station vary over a range of ~15 mbar for each station during the observation period, with changes occurring over 24 to 48 hour periods. These changes track those recorded by the National Weather Service (NWS) station at Rapid City (pressures corrected to sea level), suggesting that all of the variations in barometric pressure observed within the mine reflect changes in regional pressure caused by high and low pressure weather systems. The differences in absolute pressure between each of the stations appear to simply reflect the difference in elevation (i.e., depth) of the stations.

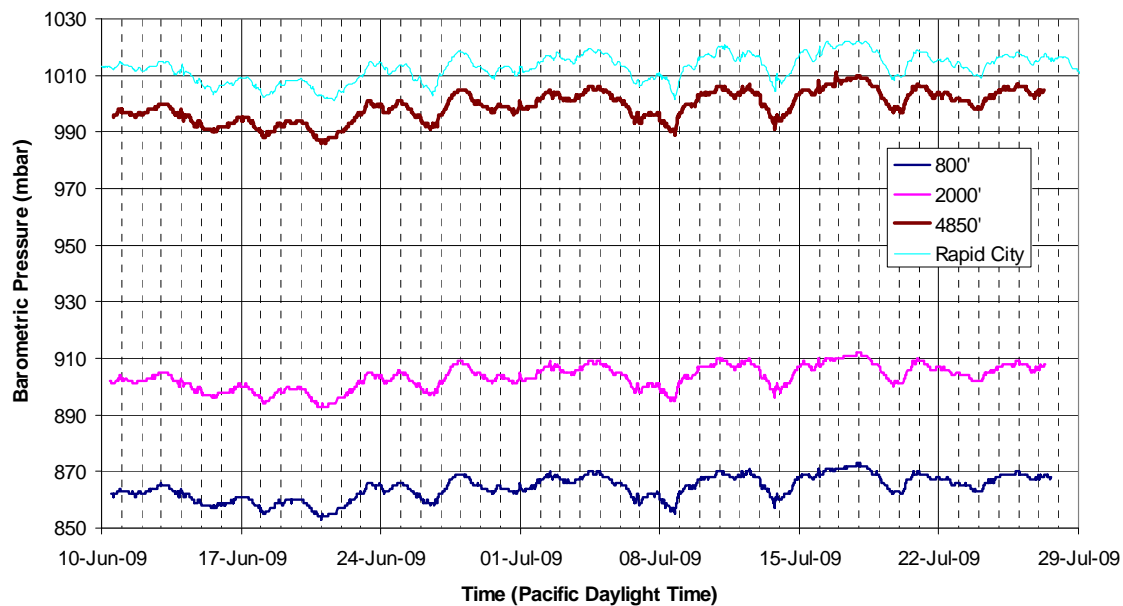


Fig. 14: Changes in barometric pressure recorded at three locations within the Homestake mine. Data for the NWS station at Rapid City (corrected to reflect an elevation at sea level) are shown for comparison. The Rapid City data are from the Research Data Archive (RDA) which is maintained by the Computational and Information Systems Laboratory at the National Center for Atmospheric Research (NCAR). NCAR is sponsored by the National Science Foundation. The original data are available from the RDA (<http://dss.ucar.edu>) in dataset number ds336.0.

Relative Humidity

Elevated relative humidity values ($>90\%$) were observed for almost all of the monitoring stations. The effects of ventilation on the drift probes are most clearly seen for the 800' and 4850' levels, which are located <400 ft (120 m) from the Ross shaft. The 4850' level was the site of a great deal of construction activity at the time of the measurements, and has the lowest relative humidity values, with most values between 70 and 90%. The 2000' drift probe, located on a side drift more than 2500 ft (760 m) from the Ross shaft, has relative humidity values typically $>98\%$, suggesting that this area is not subjected to vigorous ventilation.

The in-rock probes all ended up with very high ($>99\%$) relative humidity values. Two of the sensors (800' and 4850') initially had lower values (~ 90 - 95%) that progressively increased with time until reaching stabilized values near 100% relative humidity.

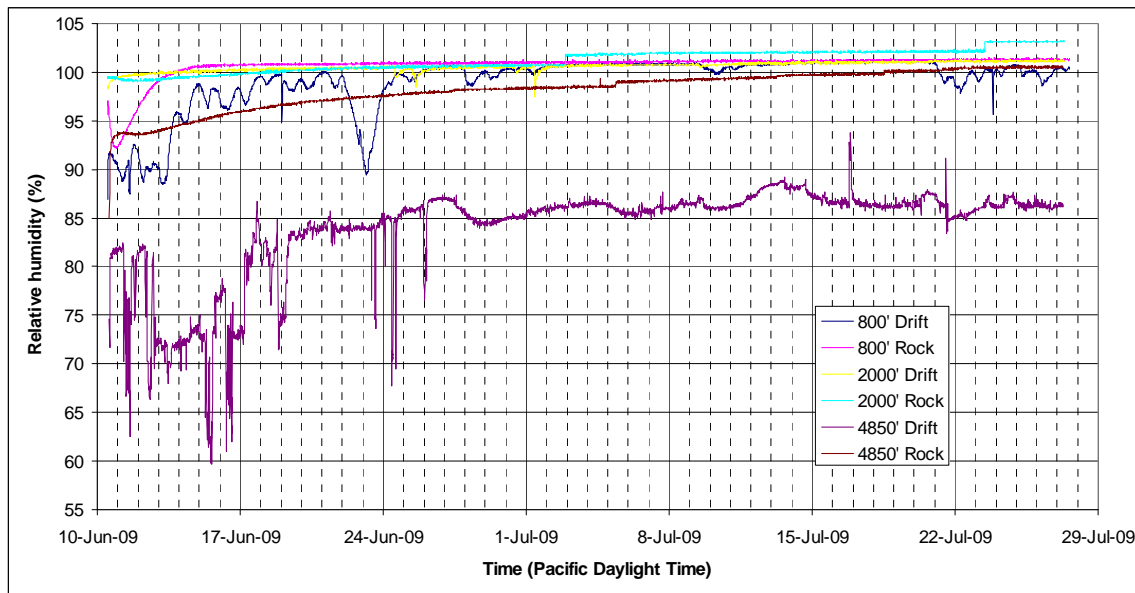


Figure 15: Relative humidity measurements for in-drift and borehole probes at three levels of the Homestake mine.

Concluding Remarks

The Homestake mine is undergoing an exciting transformation from the largest gold mine in North America to a world-class underground science laboratory. One of the proposed science facilities being evaluated is the use of the large vertical extent of the mine to host flow experiments to study the behavior of vertically migrating CO_2 , its potential interaction with reservoir and cap rocks and well cement, and the effects of microbes on CO_2 . A number of existing vertical bores were examined at the mine as potential hosts for vertical flow columns. These bores were limited in diameter, vertical extent, and accessibility, prompting the decision to opt for a new dedicated vertical bore that could be specifically designed for the DUSEL CO_2 facility.

Measurements of temperature, barometric pressure, and relative humidity were conducted at the 800', 2000', and 4850' levels. Temperature measurements made in boreholes off of these drifts yielded a temperature gradient ($12^\circ\text{C}/\text{km}$) that is quite a bit lower than previously reported values (ranging from 19.0 to $23.4^\circ\text{C}/\text{km}$). Additional measurements are recommended to resolve this apparent discrepancy, which may be due to changing conditions in the mine that have resulted in unequilibrated temperatures being recorded in 2009. Barometric pressure values vary as a function of mine elevation, and changes in pressure appear to be directly linked to regional weather patterns. Relative humidity values are high ($>99\%$) in within the rock, but are variable in the drifts resulting from ventilation effects. The results of this work will support efforts of the DUSEL CO_2 science team to locate and design their proposed underground facility at Homestake.

Acknowledgments

We thank Kevin Lesko and Joe Wang for providing us with the opportunity to conduct this study. We thank Jaret Heise, Tom Trancynger, Tom Regan, Jason van Beek, Jason Rosdahl, Larry Stetler, and Kathy Hart for their assistance at the Sanford Lab. We also

thank Curt Oldenburg, Catherine Peters, and Joe Wang for their comments on a draft of this report. This work was supported by Laboratory Directed Research and Development (LDRD) funding from Berkeley Lab awarded to the Nuclear Sciences Division, provided by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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