Sullivan Mine Fatalities Incident: Technical Investigations and Findings [1]

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ABSTRACT

In May 2006, four fatalities occurred in an ARD monitoring station at the toe of the No. 1 Shaft waste rock dump at the closed Teck Cominco Sullivan Mine near Kimberley, British Columbia, Canada. A panel was formed following the fatalities to investigate the technical aspects of the incident and disseminate findings to the mining industry. Beginning in August 2006, the dump was heavily instrumented and characterized in stages to test the initial hypothesis that changes in ambient meteorological parameters controlled dump respiration and to understand how air flows through the dump. Two drilling programs and one round of geophysical resistivity surveys were conducted to provide greater understanding of internal conditions. Automated and manual measurements gathered a variety of data, including air velocity and gas composition in the pipe connecting the toe drain and monitoring station; site meteorology; cover moisture content and temperature; and, internal temperature, gas composition, and pressure potential at thirty-four locations. The collected data clearly show the overall effects of air entry, oxygen consumption and the release of oxygen-deficient gas. However, geophysical studies and supporting drilling provide evidence for substantial heterogeneity within the dump, and patterns of snowmelt on the dump surface indicate exit points for preferential gas flow. This paper discusses the investigation program and the major results of two years of monitoring, including overall effects and the influence of heterogeneity.

Additional Key Words: dump respiration, characterization, mine waste

INTRODUCTION

During May 15 – 17, 2006, four fatalities occurred at the partially reclaimed No. 1 Shaft Waste Dump (WD1) at the closed Teck Cominco Sullivan Mine near Kimberley, British Columbia, Canada. The fatalities occurred at the toe of the dump in a seepage monitoring station that was often used, even as recently as one week prior to the fatalities, without incident.

An initial investigation showed that the fatalities were caused by depressed oxygen and correspondingly elevated levels of carbon dioxide of inorganic origin. Aerial thermal imagery did not reveal any dump hot spots. Additional details on the initial investigative response and background of the WD1 can be found elsewhere (Dawson et al., 2009). Based on the initial investigation, it was hypothesized that the 400 mm pipe connecting the drain to the monitoring station was the primary conduit between the atmosphere and dump waste rock, and that changes

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in atmospheric conditions resulted in *in situ* waste rock pore gases entering the monitoring station. Monitoring instrumentation was installed in two phases to investigate the respiration behavior of the dump. Implemented in August 2006, the initial phase of the investigation involved monitoring the dump cover, site meteorology and the monitoring station. This monitoring is continuing and the overall program was significantly expanded in March 2007 and May 2008 with additional instruments to examine internal dump temperatures, pressures, and gas composition.

MATERIALS AND METHODS

The initial installation of instruments in the technical investigations occurred in August 2006. Automated instrumentation monitors air velocity in the 400 mm pipe. Gas composition, pressure and temperature are measured at three locations: 2.4 m up the 400 mm pipe, at the end of the pipe, and at approximately waist height in the monitoring station. A meteorological station is located on a mid-slope bench above the monitoring station, recording air temperature, relative humidity, wind speed and direction, net radiation, barometric pressure and rainfall. Soil moisture and temperature are monitored continuously in the till cover at two locations on the slope.

In March 2007, six boreholes were drilled (air rotary) and instrumented to allow for the measurement of temperature, differential gas pressure and air composition at several depths within each hole using the Solinst continuous multi-channel tubing (CMT) system. To check shallow conditions (up to a depth of approximately 6 m) at other locations across the dump, a series of ten additional "push-in" gas piezometers were placed through the cover and into the dump. Collection of internal temperature and pressure data is automated at the six original boreholes. Gas composition is collected manually from all boreholes and push-ins. The differential gas pressure is the pressure difference between the atmosphere and the dump interior; henceforth this will simply be referred to as the pressure.

A geophysical survey of the site was conducted in October 2007. Resistivity measurements were made along ten transects on the dump to investigate dump heterogeneities and preferential pathways inferred from internal gas composition analysis.

In May 2008, an additional eleven boreholes were drilled and four additional push-in piezometers were installed to expand the investigation of internal conditions. Solinst CMT was again used to complete the boreholes, which were drilled by both air rotary and sonic methods. The May 2008 installation was conducted to better understand the causes of dump heterogeneities shown in the geophysical survey, and to further characterize the dump to support a decision on a final remediation plan.

In October 2008, the Monitoring Station was removed and replaced by a continuous section of drainage pipe with a U-trap; the intent is that the static water levels in the U-trap prevent the drainage pipe from being a conduit between the dump interior and the atmosphere. The U-trap water level is confirmed with automated readings from a conductivity meter and a water level sensor.

All automated systems are controlled by Campbell Scientific dataloggers. Automated data is recorded every 15 and 60 minutes; the hourly data is the basis for the results presented in this paper. Manually collected data is retrieved once per week. Additional details on instrumentation and installation methodology can be found in previously presented material (Phillip and Hockley, 2007a;, Phillip and Hockley, 2007b; Phillip et al., 2008).

RESULTS AND DISCUSSION

Respiration Investigation

Initial results reported a relationship between air temperature and air velocity (Phillip and Hockley, 2007a; Phillip and Hockley, 2007b; Phillip et al., 2008). The influence of air temperature on dump respiration has been noted by others (Smolensky et al., 1999; Hockley et al., 2000). Air temperature controls respiration by affecting the relative density of the interior pore gases. From roughly fall to spring, the internal air is warmer and thus less dense than the surrounding atmosphere and rises up through the dump and exits the cover system, pulling in air behind it. During the summer the opposite condition exists.

Recently collected data have continued to demonstrate the control that atmospheric air temperature has on dump respiration. This control is shown in the relationship between air temperature and air velocity in the Monitoring Station 400 mm pipe. The air flow through the 400 mm pipe is designated as a positive velocity if the flow is into the pipe and drain; negative, if out of the pipe and into the monitoring station. A comparison of air temperature and air velocity reveals a strong relationship (see Figures 1 and 2) with a pivot point of 10 – 12°C.

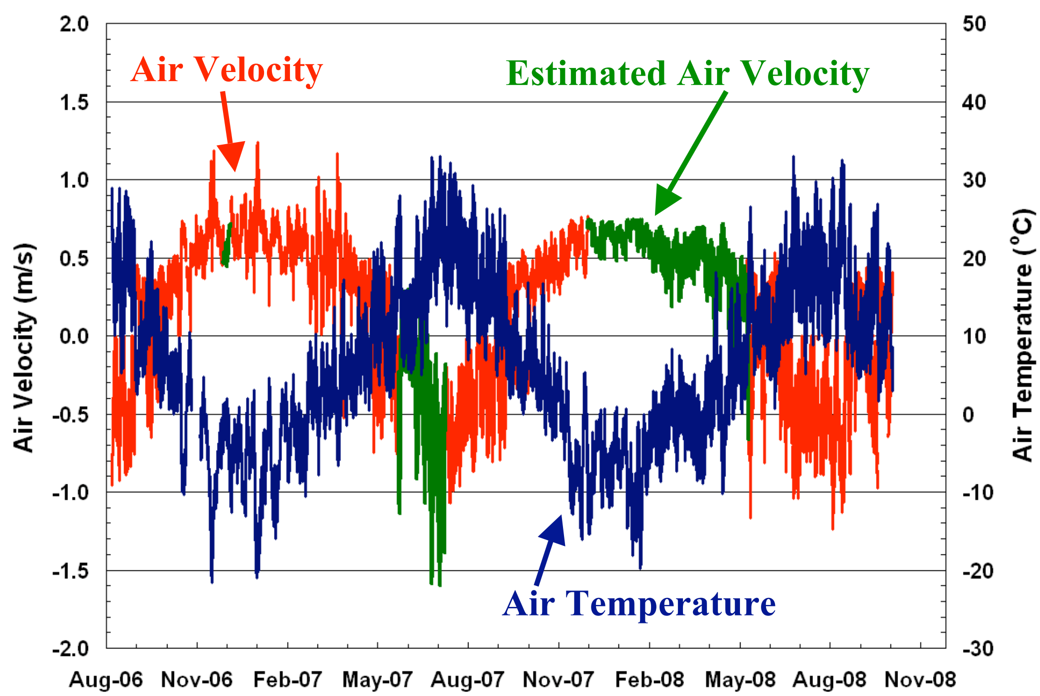

Figure 1. A Comparison of Air Temperature and Air Velocity

During periods of sensor failure, the air velocity is estimated based on the relationship between air temperature and air velocity, shown in Figure 2.

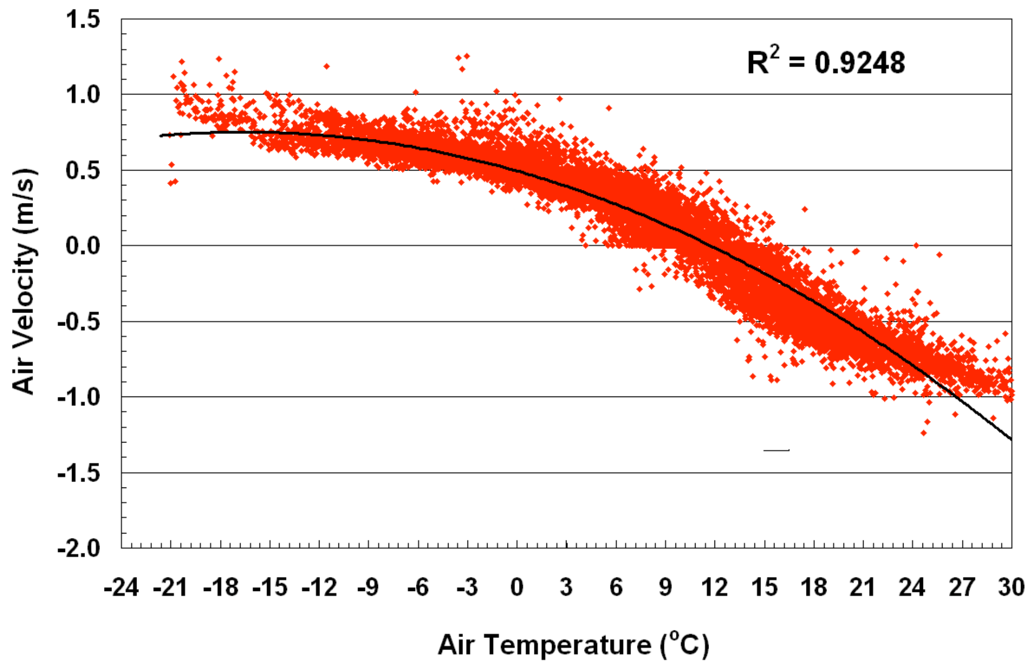

Figure 2. Air velocity versus air temperature.

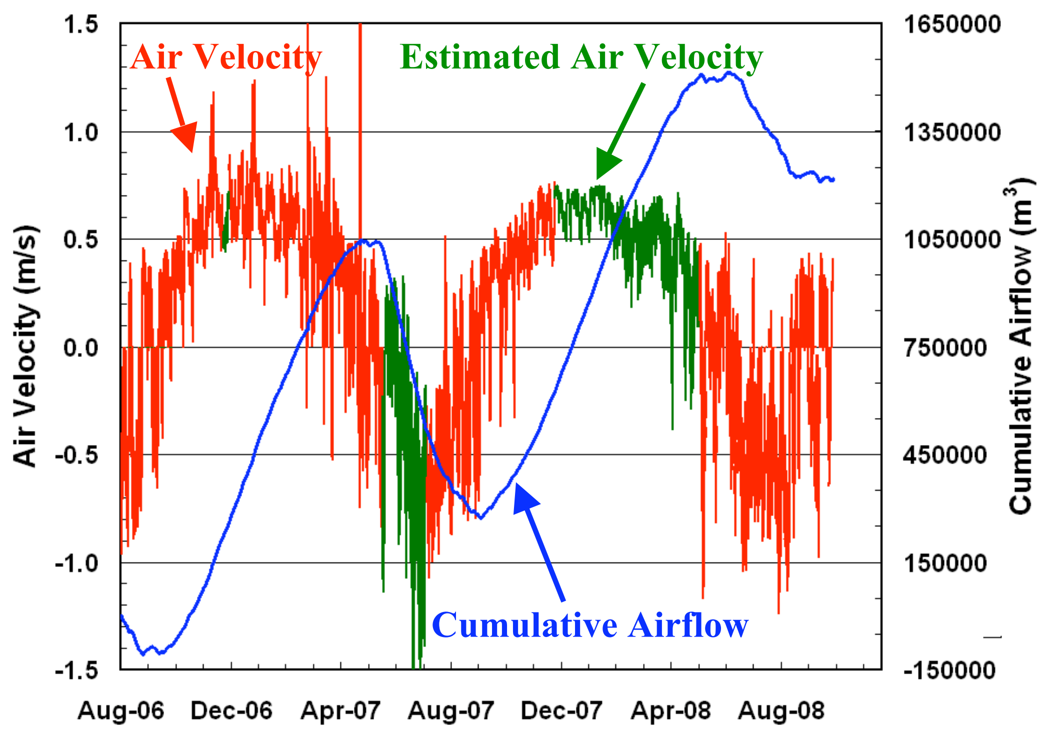

Figure. 3. Air velocity and cumulative airflow.

The volume of air moving into or out of the dump can be calculated on the basis of the air velocity and the cross-sectional area of the 400 mm pipe that does not contain drainage. Figure 3 shows the cumulative airflow volume from August 2006 to June 2008. The change in cumulative airflow during the 2007-2008 winter is less definite than the previous winter because so much of it is based on estimated air velocity; in addition, there were actually brief periods with no airflow when the 400 mm pipe was flooded due to an ice jam downstream in the drainage pipe. Regardless, the calculated cumulative airflow for the 2007-2008 winter is similar to the previous: approximately 1.2M m^3, or four times the estimated dump void space.

The movement of air into and out of the dump through the 400 mm drainage pipe is very dynamic. Air velocity values and automated gas composition readings correspond well and demonstrate how quickly a working environment can become hazardous (see Figure 4).

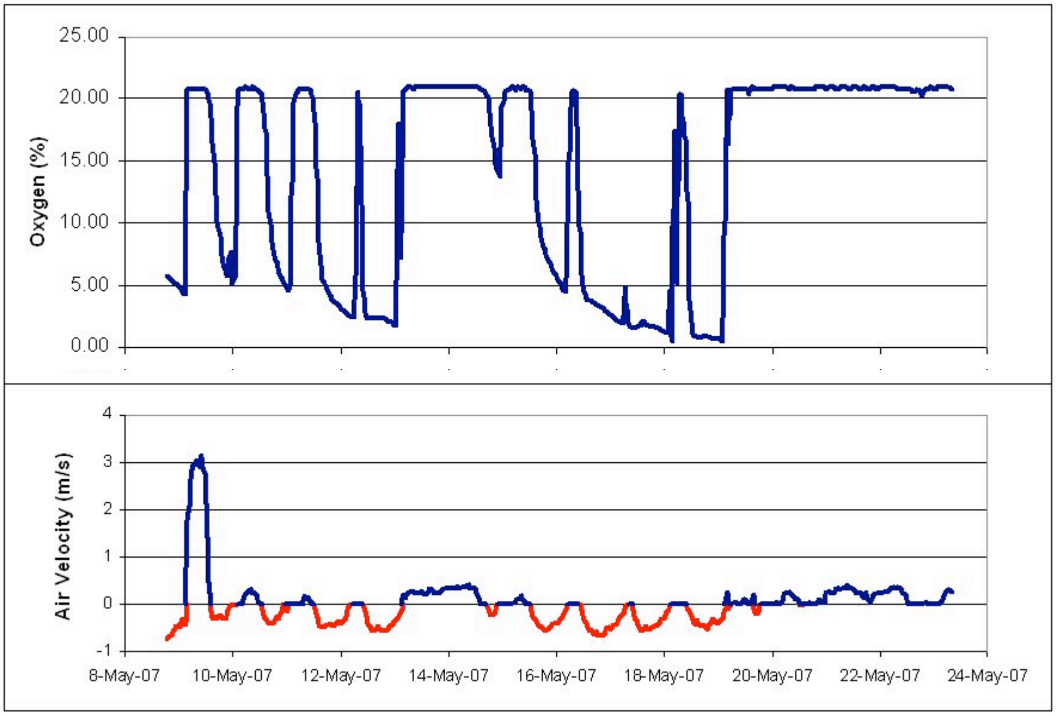

Figure 4. Changes in monitoring station oxygen composition in response to air velocity. The top graph is oxygen content; and, the bottom graph, air velocity. Positive air velocity is blue; negative is red.

The No. 1 Waste Dump airflow pivot point, the temperature at which airflow changes direction, has steadily increased with each periodic evaluation. This could possibly be due to shifts caused by a larger data set. However, the core temperature in BH-1A and BH-1B has increased from approximately 16 to 18 °C in the little more than one year of monitoring, and it is logical to conclude that the pivot point is shifting because the WD1 internal temperature is increasing. Subsets of the air velocity and air temperature data were examined for increases in the pivot point. The subsets were during the three transition periods in the period of record: Fall 2006, Spring 2007 and Fall 2007. Each subset contains the same number of days. For the three periods above, the pivot points were 10.9, 11.1 and 12.4 °C, respectively. While the analysis performed to date treats the air velocity-air temperature relationship as unified, it is important to know that it is dynamic and at some point must be thought of as a result of a number of relationships.

Internal Conditions Investigation
With collection beginning in March 2007, the internal temperature, pressure and gas composition data confirmed the respiration model. The pressure gradients, gas composition and, temperature showed a system with inflow at the toe from fall to spring and the opposite the remainder of the year. This pattern is not limited to a single preferential pathway, but is generally uniform throughout the dump.

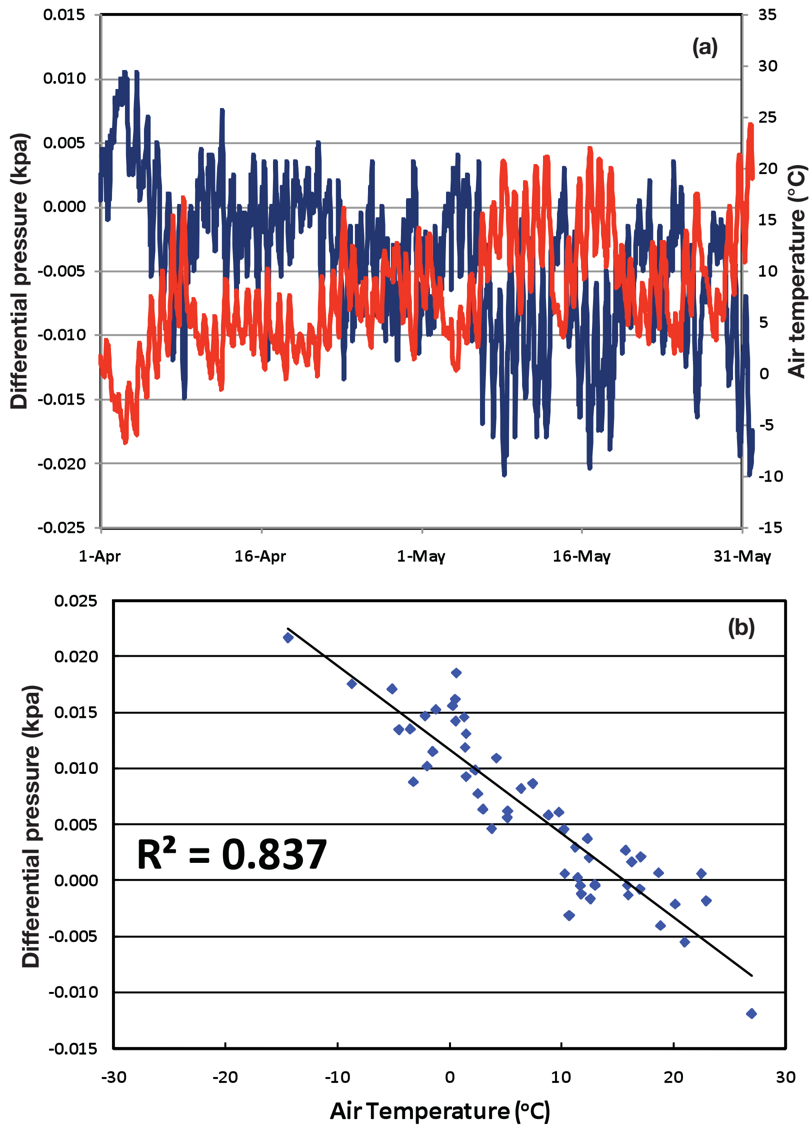

Figure 5. Borehole 2B pressure and air temperature (a), and pressure vs air temperature (b).

Analysis of changes of internal pressure relative to air temperature showed a relationship similar to air velocity and air temperature seen in Figure 1 (see Figure 5a). When pressure is plotted against air temperature, the resulting correlation is taken as an indication of the dump's interior air permeability (see Figure 5b). Based previously on gas composition, the lower CMT ports of borehole 2B were believed to reside in a preferential pathway from the toe drain into the main body of the dump. The high correlation seen in Figure 5b supports this. This same method supports the existence of other preferential pathway observations, as well as areas in the dump believed to be isolated.

The analysis of drill cuttings clearly showed that both sulfide minerals and carbonate minerals are present in the rock. The sulfide minerals were expected. The carbonate minerals were not expected, but there was evidence of carbonate in most of the chemical analyses, and the carbonate mineral calcite was identified in about half of the mineralogical samples; the percent sulfide and carbonate were less than 3% and 1%, respectively. Carbonate minerals were also found in samples of the till material that was used to cover the dump and which form the base of the drainage collection system running beneath the dump toe. These results conclusively demonstrate that air within the dump is reacting with sulfide minerals, leading to the depletion of oxygen and generation of acid; consumption of acid by carbonates produces carbon dioxide.

Internal oxygen and carbon dioxide concentrations are measured and have an inverse relationship in the pore gas due to well-known geochemical reactions. Oxygen concentrations measured within the dump ranged from values typical of normal air (about 21%) to near zero. Carbon dioxide concentrations ranged from near zero to about 5% in most locations, but were as high as 21% in one borehole. Analysis has shown that in WD1 the resulting change in gas composition has a very minor effect on pore gas density. Respiration is driven by density differences due to temperature, not changes in gas composition.

Premature Snowmelt Areas

During the March 2007 drilling, several premature snowmelt areas (PSAs) were observed and mapped across the dump surface (see Figure 6). It was theorized that the PSAs were vent areas where warmed internal air would exit the dump. Manual monitoring during the 2007-2008 winter discovered five discrete vents on the surface of the dump. At the surface, the vents exhaust depleted oxygen as low as 6%, but oxygen values return to normal atmospheric conditions with 15 cm from the surface. Manual monitoring in November 2008 discovered vents exhibiting similar behavior on another reclaimed waste dump at the Sullivan Mine. These vents occur at cracks in the cover, and at gaps in the cover around fence posts, well casings, and survey stakes.

Figure 6. Photo of a No. 1 Dump Premature Snowmelt Area

Geophysical Surveys

When drilling the boreholes in March 2007, recovery of drill cuttings varied widely. With the two deepest holes there were intervals as much as 3 m with no recovery, which suggests heterogeneity within the dump. To investigate the possible heterogeneities, ten resistive geophysical surveys were completed on the dump surface in October 2007. One survey was performed on a smaller and older dump in the Lower Mine Yard, the North Dump. The North Dump contained a uniformly conductive waste material; however, WD1 was shown to be very heterogeneous in nature (see Figure 7).

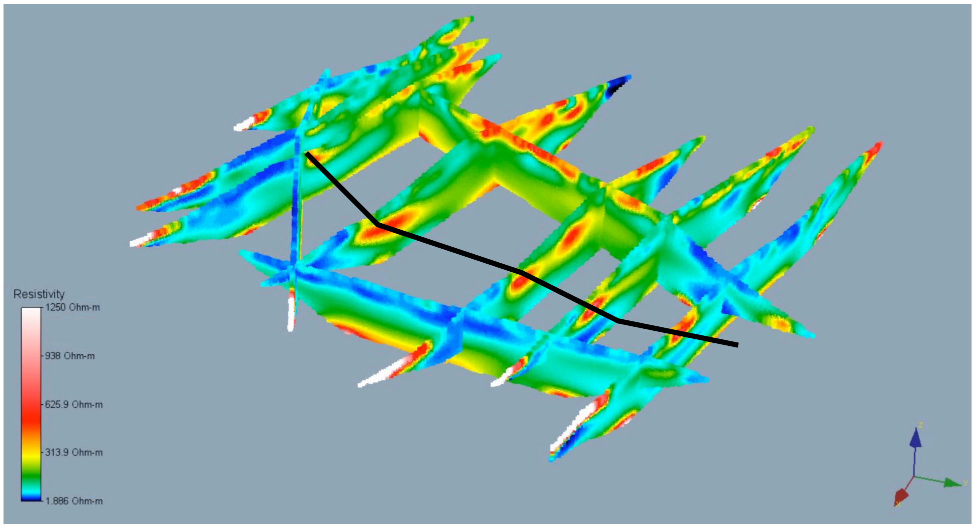

Figure 7. Resistivity survey results for the No. 1 Waste Dump. The black line highlights a resistive body that appears to run through the dump under the mid-slope bench. (red is resistive and blue is conductive)

Additional Dump Characterization

The drilling program in May 2008 showed a waste rock dump comprised of "barren" waste rock, sulfidic waste rock, trash, debris (cables, timbers) and even a pocket of calcine. The end-dumped construction was quite evident with material becoming coarse with depth. The resistive body highlighted in Figure 7 is believed to be the accumulation of large rocks at the former dump toe prior to regrading in 2004. The conductive areas along the lower periphery of the dump are materials that would have been disturbed and pushed down during the same regrading effort.

The most recent monitoring data and the additional internal temperature monitoring locations have led to further insights about the processes occurring within the dump, in particular their heterogeneity. New boreholes through the thickest portion of the dump have shown core temperatures of approximately 20 °C. New boreholes located on the basis of snowmelt patterns have found localized temperatures of 27 °C along the northern crest.

With the different temperatures come different airflow regimes in the dump. While the areas of 18 and 20 °C core temperatures may be part of the general flow system shown in Figures 1 through 3, the 27 °C area along the northern crest appears to be part of a different flow system. At times when the pivot point is exceeded and air is falling through the dump and exiting the 400 mm pipe, along the northern crest the internal pore gas is still rising through the dump, an observation supported by pressure gradients and gas composition analysis.

Interim Remediation Measure

In October 2008, the removal of the Monitoring Station and installation of the U-trap was expected to change the internal gas composition by eliminating the primary conduit between the dump interior and the atmosphere. A brief ice and water blockage of the Monitoring Station's 400 mm pipe in early 2008 did result in a drop of oxygen levels within the dump. However, review of pressure and gas composition data since installation of the U-trap has not shown a significant difference between November 2008 and 2007. It is therefore possible that while the 400 mm pipe offered an easy conduit to the atmosphere, it is by no means the primary conduit and has minimal effect on dump respiration.

CONCLUSIONS

In response to four fatalities at the Sullivan Mine No. 1 Shaft Waste Dump, an extensive investigation was initiated to understand the processes that resulted in low-oxygen, high carbon dioxide gas entering the monitoring station. With a pivot point of approximately 10-12 °C, air temperature is observed to be the dominant respiration control. Conventional geochemical reactions explain the consumption of oxygen and generation of carbon dioxide; however, the resulting gas density change is very small and unlikely to be a major driver in gas flow. Summer and winter air temperature extremes straddle the moderate internal temperature profile, confirming air temperature as the dominant controlling factor for air flow at the No. 1 Shaft Waste Dump.

Changes to internal pressures have been used to understand relative permeability and confirm preferential pathways. Geophysical surveys and a drilling program helped characterize the dump interior, which is heavily influenced by end-dumping construction. Vents discovered on the surface and the lack of significant change to internal gas composition and pressures in response to the U-trap installation suggests that the 400 mm pipe was not the primary conduit between the atmosphere and the dump interior.

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