SULLIVAN MINE FATALITIES INCIDENT: PRELIMINARY TECHNICAL INVESTIGATIONS AND FINDINGS

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ABSTRACT

During May 15 – 17, 2006, four fatalities occurred at a partially reclaimed waste rock dump 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 is connected hydraulically, via a pipe and dump toe drain, to the covered acid generating waste rock. The monitoring station was often used prior to the fatalities and even as recently as one week prior to the incident. A panel was formed following the fatalities to investigate the technical aspects of the incident and disseminate findings to the mining industry. Since August 2006, the dump has been heavily instrumented in stages to test the initial hypotheses that changes in ambient meteorological parameters resulted in the respiration of air indicative of in situ waste rock pore space gas through the monitoring station. Automated and manual measurements gather 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 16 locations. Monitoring and data analysis under the oversight of the Technical Panel continues. Initial results have shown that atmospheric air temperature, not barometric pressure, is the dominant control on air movement between the waste dump and the atmosphere.

1. INTRODUCTION

During May 15 – 17, 2006, four fatalities occurred at the partially reclaimed No. 1 Shaft Waste Dump at the closed Teck Cominco Sullivan Mine near Kimberley, British Columbia, Canada (see Figure 1). 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.

Samples taken in the days immediately following the fatalities from within the monitoring station indicated that the air was depleted of oxygen and contained elevated levels of carbon dioxide. The concentration of oxygen was about 2% and that of carbon dioxide was about 7%. Isotopic analysis showed that the carbon source was inorganic. Thermal imagery surveys were flown and did not reveal any significant "hot spots" in the dump.

Subsequent to the fatalities of May 15 - 17, 2006, Teck Cominco sought advice from University of British Columbia (UBC) experts and from a technical consulting firm as to the potential underlying causes of the tragedy. Based on inspections of the No. 1 Shaft Waste Dump site, analyses of monitoring station air samples taken shortly after the tragedy and their knowledge of the processes that occur in covered waste dumps, both groups came to realize that movement of oxygen depleted air from the dump into the monitoring station was a likely causal factor.

Fig. 1. Location of Kimberley British Columbia, Canada

This realization led to recommendations for technical investigations into the chemical and physical processes affecting air in the No. 1 Shaft Waste Dump and monitoring station. The investigation program is being guided by a Technical Panel that consists of independent experts from UBC, staff from both the MEMPR and Teck Cominco, and their respective technical advisors.

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 in atmospheric conditions resulted in *in situ* waste rock pore gases entering the monitoring station. To investigate the respiration behavior of the dump monitoring equipment was installed in two phases. 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 with additional instruments to examine internal dump temperatures, pressures, and gas composition.

2. BACKGROUND

The No.1 Shaft Waste Dump was created during the 1940's to 2001, principally by the deposition of waste rock from the No. 1 Shaft. The dump curves along the slope below the shaft in a southwest to northeast orientation (see Figure 2). The height from the upper flat portion of the dump to the toe is approximately 55 m. The dump is comprised of approximately 2.6M t of primarily sulfidic waste rock. The estimated dump volume is 1M m^3 with approximately 30% void space.

The upper mine underground workings of the Sullivan Mine were entered through several horizontal drifts to access the ore body. As the workings went deeper underground a steeply inclined shaft (No.1 Shaft) was constructed to bring personnel, equipment and supplies into and out of the mine using a hoist positioned at the surface. A skip connected to the hoist also had the capability of removing waste rock from the mining levels. At surface the waste rock was dumped over the side of the bank downhill of the hoist to form the No.1 Shaft Waste Rock Dump. Initially the rock was less than 15 cm in size to accommodate the loading of narrow gauge underground rail cars. The waste rock could also have high moisture content if it originated from the lower levels of the mine.

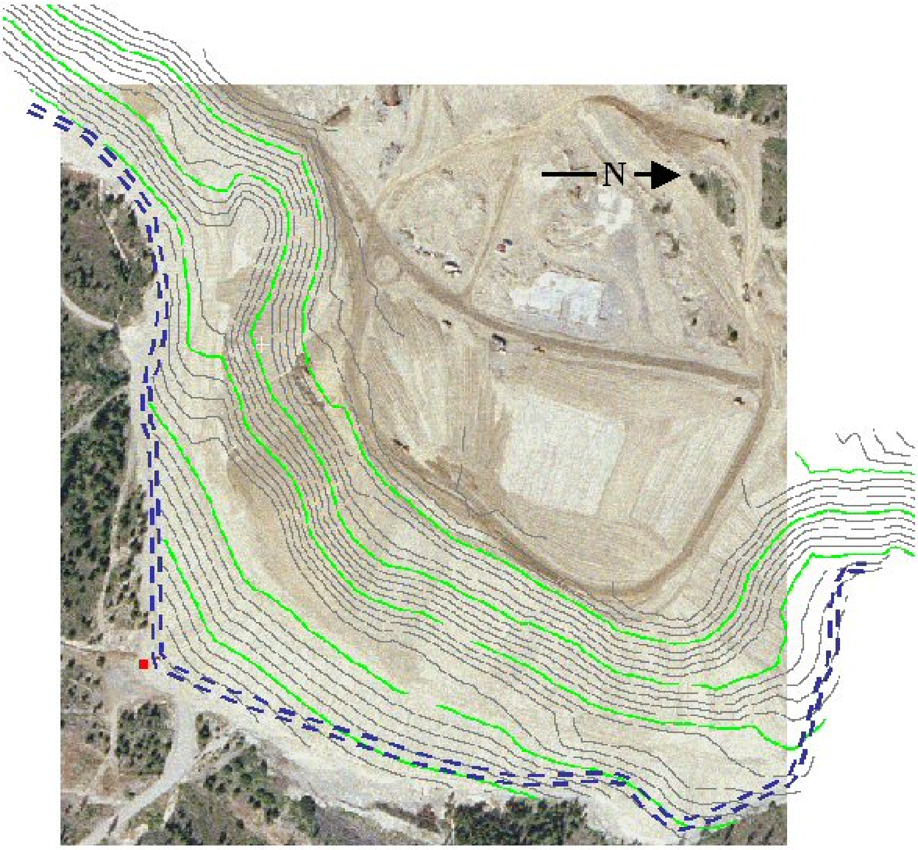

Fig. 2. **No. 1 Shaft waste dump. The drain, formerly the ditch, is shown with blue dashed lines along the toe. The monitoring station is the red square at the southeast corner of the dump.**

In the 1980s the mining methods started to include some mechanized mining using large rubber tired equipment to drill and muck the rock. The waste rock was still removed using the No.1 Shaft hoisting system but the rock was coarser. The oversize rock was placed in designated areas of the dump. The waste rock dump also was used to dispose of other waste materials from the mine such as domestic garbage, industrial wastes such as steel, plastic, wood, etc., spent or residual shotcreted materials, glacial till and other site debris.

Teck Cominco began to examine the water quality downstream of the waste dump and it was found to be affected by the Acid Rock Drainage (ARD) coming from the dump. To eliminate an impact on the receiving waters it was determined the ARD water coming out of the waste rock dump was to be collected and treated at Teck Cominco's Drainage Water Treatment Plant (DWTP). After examining the soils downstream of the dump it was discovered that the dump was placed on a glacial till layer of material overtopped with granular materials. The granular zones were producing springs of contaminated water. In 1995 it was decided to place a drainage ditch around the toe of the dump and collect the water in the ditch and pipe it to the DWTP. This proved to be very effective at intercepting the contaminated water and resulted in substantial improvement in the receiving water quality.

After the toe drainage ditch was put into operation it was deemed necessary to measure the flow of ARD water from the dump and to sample the water quality. This information was to be used to determine the effectiveness of the reclamation techniques. In 1995 a V notch weir was installed. However, the weir was subject to icing over and it was hard to get a water sample in the winter. In 1997 the weir was surrounded with large concrete blocks and covered by a small building. This became known as No.1 Shaft Waste Rock Dump Monitoring Station (see Figure 3a).

In 2004 the toe ditch was reworked by placing a compacted glacial till impermeable lining in the ditch and on the downstream slope. The ditch was then filled in with coarse rock over topped by finer rock followed by a filter layer of material (see Figure 3b). This was carried out to allow the waste rock to be placed up to and partially over the ditch when the dump was reprofiled for reclamation and geotechnical stability. In 2004 the waste rock in the dump was reprofiled up to and partially covering the toe drainage ditch. In 2005 a 1 m thick layer of glacial till soil cover was placed over the waste rock and the ditch. The surface or uncontaminated water would run off the dump but the contaminated water would be collected. A cross section of the filled ditch, the dump drain and the pipe connection to the monitoring station is shown in Figure 3c.

The dump cover was completed in October 2005, under wet conditions. It was left un-vegetated over the winter. In preparation for seeding, the cover was ripped in May 2006, about one week prior to the fatalities.

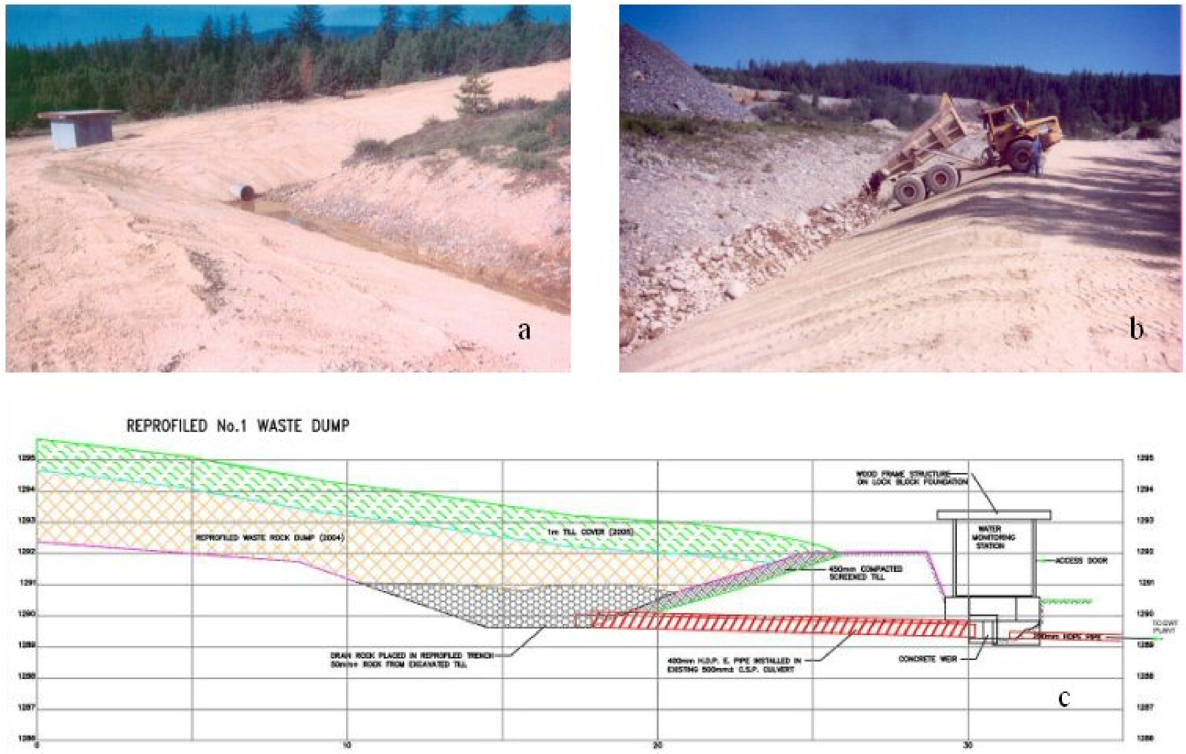

Fig. 3. **The monitoring station prior to reclamation (a).**
Drain rock being placed in the ditch (b).
Cross-section showing drain rock, waste rock and till cover in former ditch with 400 mm pipe conveying seepage to monitoring station (c).

3. MATERIALS AND METHODS

The Phase 1 installation of monitoring equipment, in August 2006, included instruments to automatically track conditions within the monitoring station. 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. Gas composition is measured with a Nova Analytical oxygen and carbon dioxide analyzer and solenoid sequencer. Temperature and pressure are monitored with the Campbell Scientific 107B and CS100 sensors, respectively. Air flow into and out of the 400 mm pipe is measured with an RM Young 85000 ultrasonic anemometer. Drainage flow is monitored by measuring the weir water height with a Campbell Scientific SR50 ultrasonic ranging device. All of the monitoring instruments within the monitoring station are operated remotely from a heated instrument shed located a short distance downhill. All sensors are controlled by Campbell Scientific dataloggers.

The weather station was installed on a mid-slope bench above the monitoring station. The weather station measures air temperature and relative humidity (Vaisala HMP45C212), wind speed and direction (RM Young 05103), net radiation (Kipp & Zonen NR Lite), and rainfall (Texas Electronics TE525).

Soil moisture and temperature within the till cover are monitored continuously at two locations: adjacent to the weather station and above it near the top surface of the dump. Soil moisture and temperature are measured with Campbell Scientific 616 and 107B sensors, respectively. A more complete areal understanding of till cover moisture content is gathered using the manual Sentek Diviner2000™. Figure 4 shows the location of the initial monitoring systems25

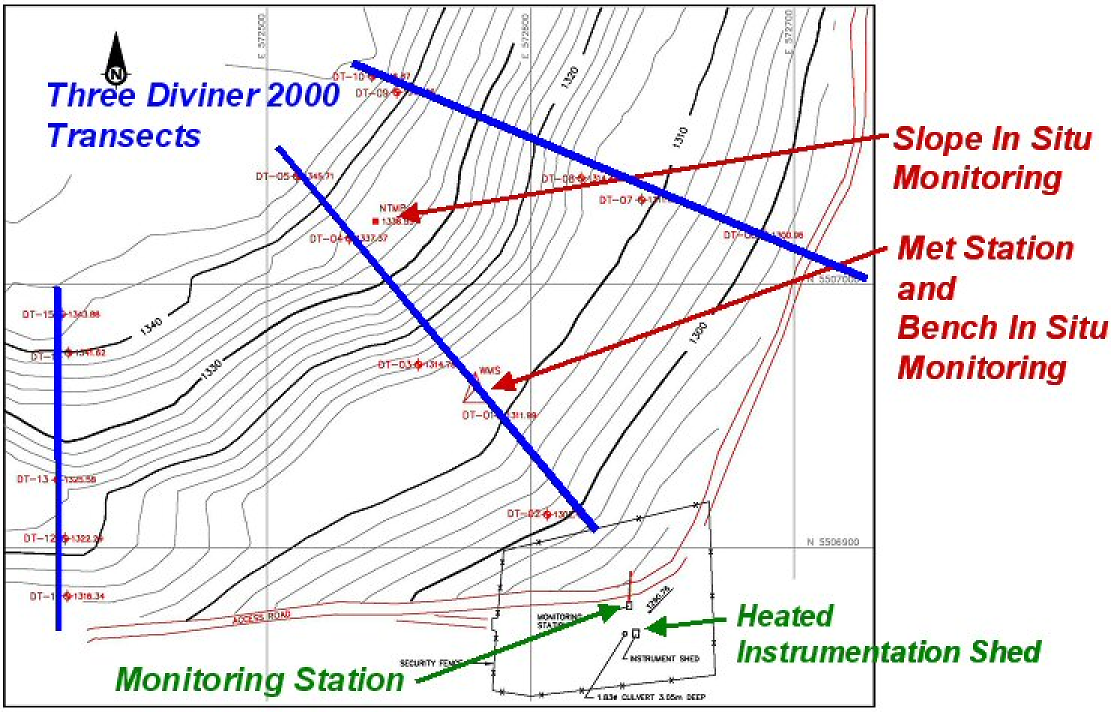

Fig. 4. Layout of Phase 1 monitoring system

The Phase 2 installations (March and April 2007) were directed towards monitoring conditions within the dump (see Figure 5). Six boreholes were drilled and installed with the Solinst continuous multi-channel tubing (CMT) system to allow for the measurement of temperature, differential gas pressure and air composition at several depths within each hole. Bentonite seals were used to isolate the gas sampling locations. Temperature and pressure readings are automated and made with Campbell Scientific 107B and Setra 264 sensors, respectively. The temperature probes were attached to the outside of the CMT. Differential gas pressure (automated) and gas composition (manual) readings are made via the CMT channels. Drill cuttings were collected and analyzed in the field for paste pH as a screening tool; select samples were then submitted to laboratory analysis, including acid-base accounting, shake flask extraction, and x-ray diffraction.

To check conditions at other locations across the dump, a series of ten additional "push-in" gas piezometers were placed through the cover and into the dump. A 150 mm diameter casing, slotted at approximately 7 and 3.5 m depths, was pushed through the cover and into the waste rock using a vibratory attachment on an excavator. Stainless steel sampling tubes (12.5 mm diameter), with temperature probes attached, were completed within the casing to allow for manual gas composition, temperature and differential pressure measurements. Bentonite seals were used to isolate the gas sampling locations.

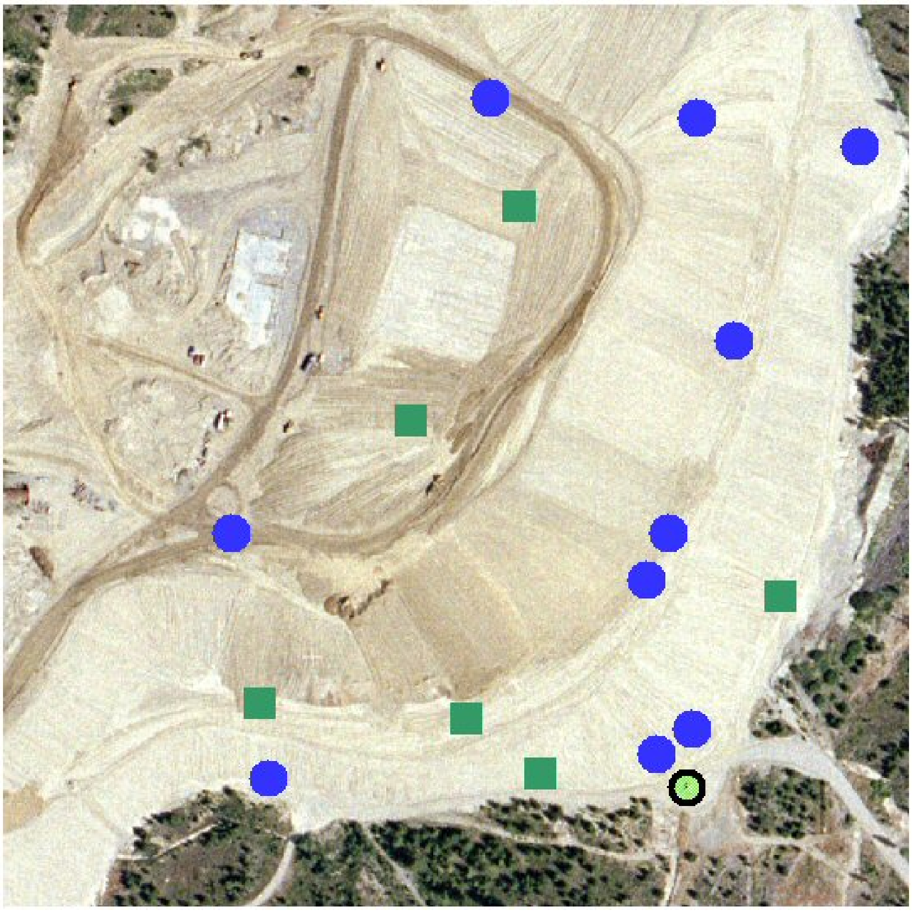

Fig. 5. Layout of Phase 2 monitoring locations. The boreholes and push-in piezometers are represented by squares and circles, respectively. The monitoring station is highlighted and circled in black.

Data from the monitoring station, weather station, boreholes and two push-ins' are collected at 15-minute, hourly and daily intervals. Soil station data are collected every six hours. The data are collected by dataloggers, which are downloaded remotely. Data is downloaded weekly and undergoes quality control processing approximately every quarter.

4. RESULTS AND DISCUSSION

4.1 Phase 1 Data

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.

Air velocity and monitoring station gas composition correspond well. Normal atmospheric oxygen and carbon dioxide levels correspond to periods of positive air velocity, but drop to levels recorded following the incident (see Figure 6) during negative air velocity periods. The low oxygen and high carbon dioxide concentrations recorded exiting the dump, are expected for a sulfidic waste system that produces ARD. Pyrite oxidation consumes oxygen and produces acid, which can react with carbonate minerals to produce carbon dioxide gas.

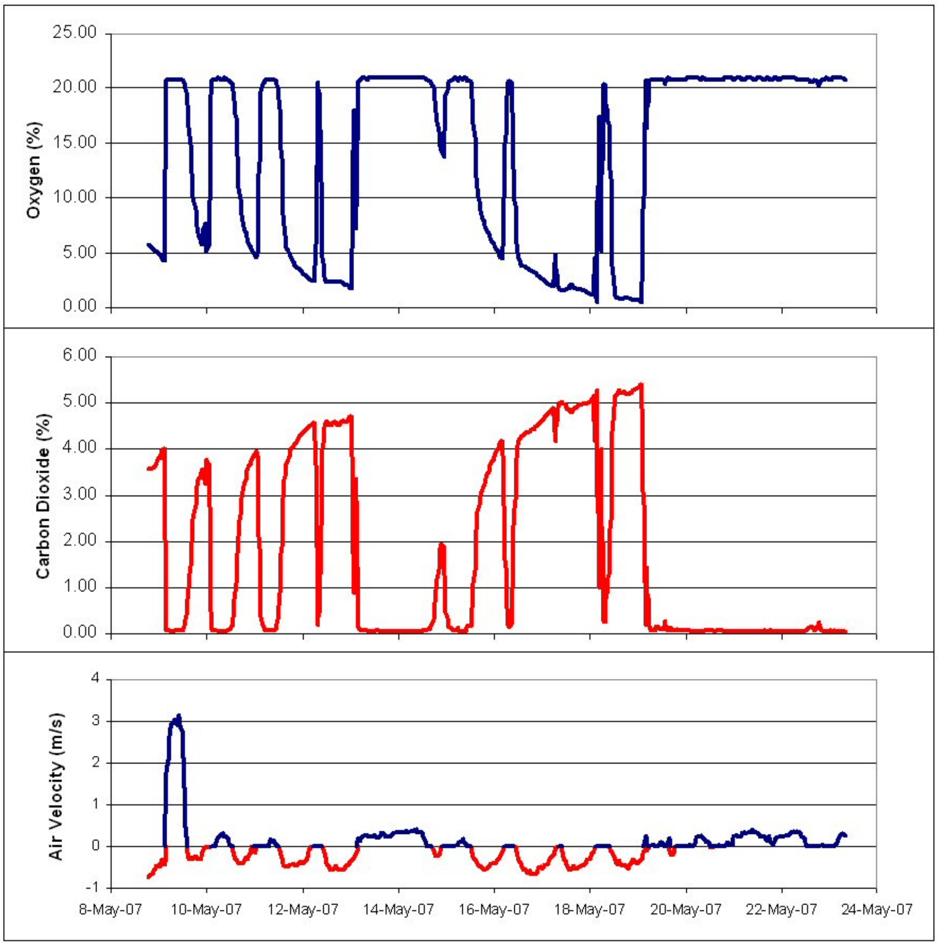

Fig. 6. **Changes in monitoring station gas composition in Response to air velocity. The top graph is oxygen content; the middle, carbon dioxide; and, the bottom graph, air velocity. Positive air velocity is blue; negative is red.**

It was expected that changes in barometric pressure could control air movement through the 400 mm pipe. The influence of barometric pressure on dump respiration has been noted by others (Hockley et al*.* 2003). If barometric pressure controlled respiration, a drop in barometric pressure would result in the dump internal pressure being greater; as the pressure works to equalize, internal gases would exit the dump. A comparison of barometric pressure and air velocity does not reveal a strong relationship (see Figure 7).

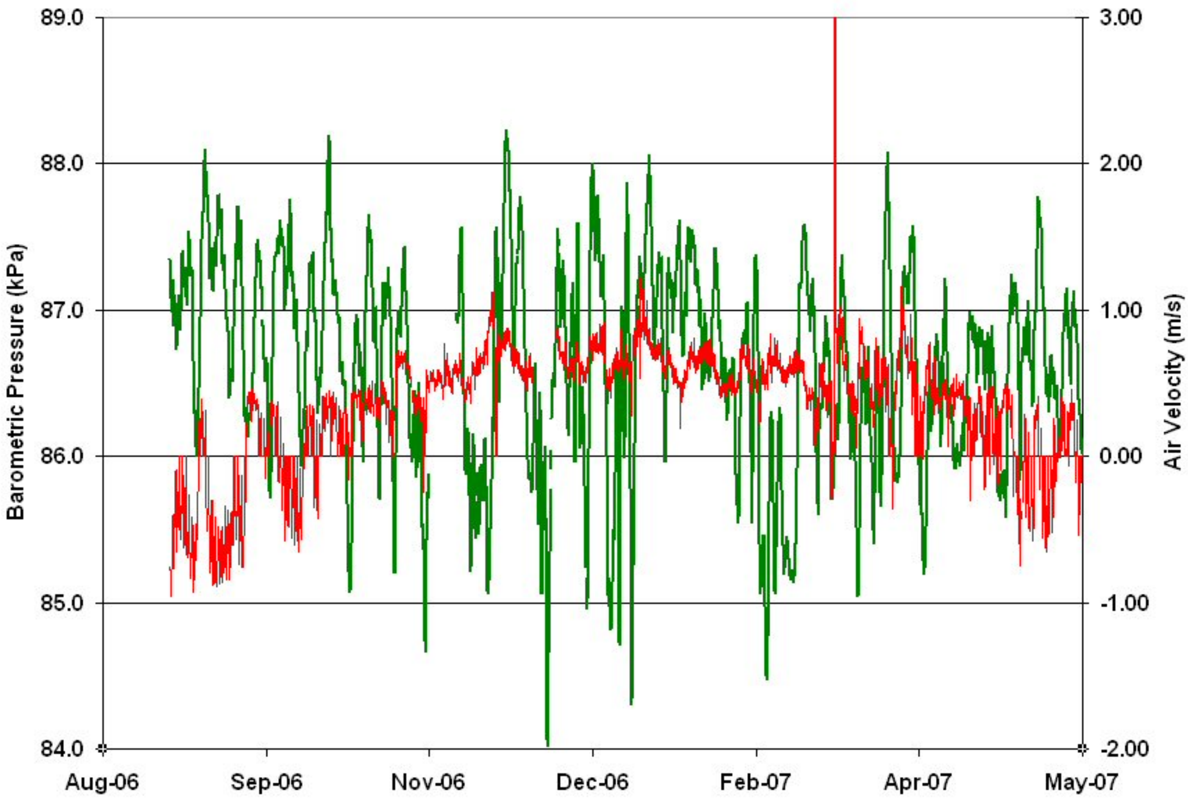

Fig. 7. Barometric pressure (green) and air velocity (red)

An alternate hypothesis was that changes in air temperature could control air movement through the 400 mm pipe. The influence of air temperature on dump respiration has been noted by others (Smolensky et al. 1999 and Hockley et al. 2000). A comparison of air temperature and air velocity reveals a strong relationship (see Figures 8 and 9) with a pivot point of approximately 11 °C.

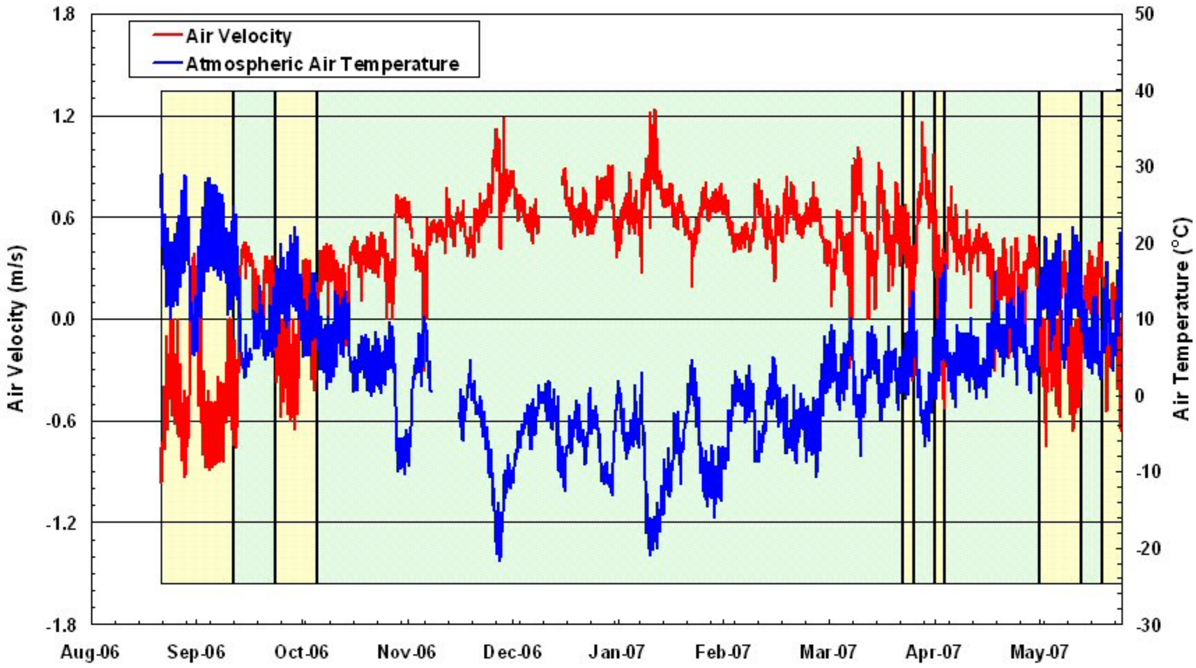

Fig. 8. **Air flow in the 400 mm pipe and atmospheric air temperature. A positive velocity indicates air was moving into the pipe; a negative velocity means air was moving out. Periods of inward flow are shaded green; periods of outward flow are shaded yellow.**

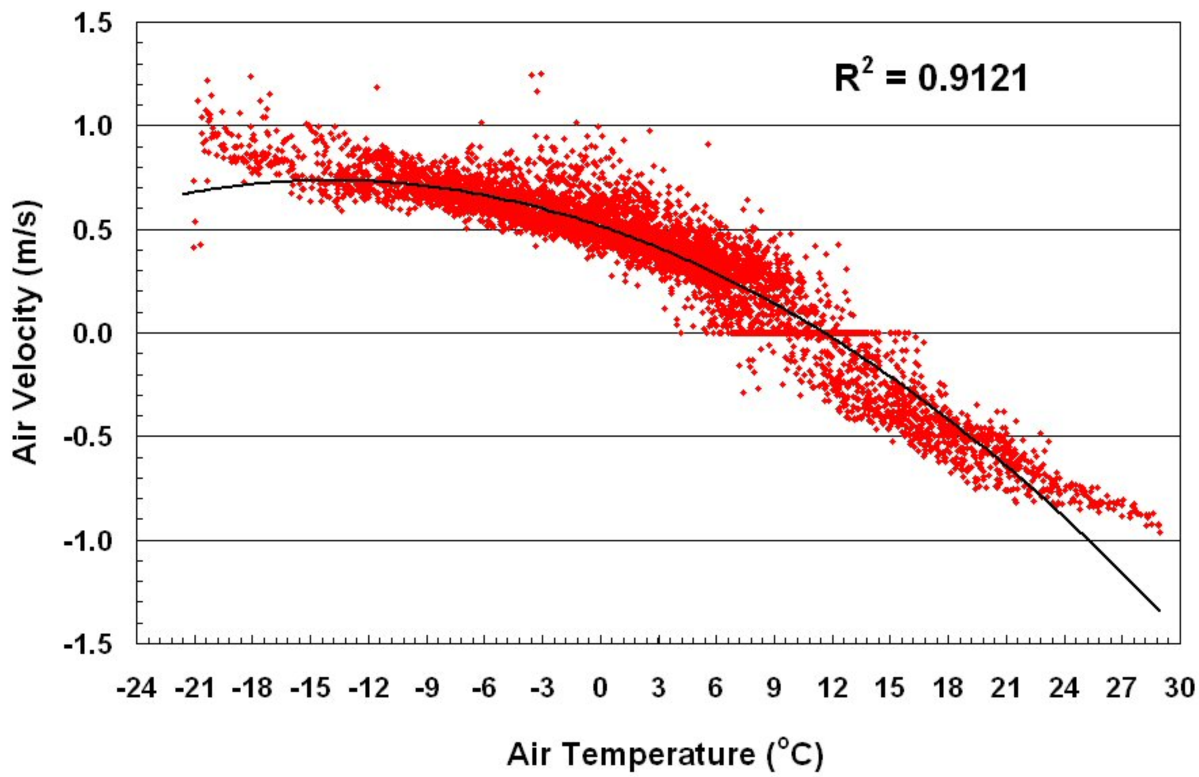

Fig. 9. **Air velocity versus air temperature**

Air temperature controls respiration by affecting the relative density of the interior pore gases. From roughly fall to spring when air temperature is less than 11°C, the internal air is warmer and thus less dense than the surrounding atmosphere and rises up through the dump and and exits the cover system, pulling in air behind it. During the summer the opposite condition is true.

At the time of the May 2006 incident, there was no air temperature or barometric pressure monitoring at the site. However, the weather station at the nearby Cranbrook airport was collecting both measurements. Based on the Cranbrook airport data, the May 13-17, 2006 period included both a sharp increase in air temperature to about 20 °C and a strong decrease in barometric pressure. It has been reported that the monitoring station was safely entered in the preceding week on May 8, 2006. The Cranbrook airport data for that date indicated a sharply rising barometric pressure and a temperature of less than 10 °C. (see Figure 10).

Fig. 10. Daily average air temperature at Cranbrook airport in May 2006. Monitoring station was entered safely on May 8, 2006.

We know now, from both the station monitoring data and the internal dump instrumentation, that air temperatures drive air movements in this system. It is reasonable to conclude that the increase in air temperatures during May 13-17, 2006 made the air around the No. 1 Shaft Waste Dump lighter than the cooler air inside the dump, and caused the air inside the dump to flow downward, out of the 400 mm pipe, and into the monitoring station. The possibility that the barometric pressure changes also contributed to the air movement in May 2006 probably can never be ruled out completely, but the dominant effect of the temperature change is clear.

Knowing the air velocity and the cross-sectional area of the 400 mm pipe that does not contain drainage, the volume of air moving into or out of the dump can be calculated. Figure

11 shows the cumulative airflow volume during the 2006-2007 winter is nearly 1.2M m^3, or four times the estimated dump void space, suggesting that a large amount of the air may not be flowing in a homogeneous nature through the dump. It is also evident that in the course of a year, more air enters the dump through the pipe than exits, most likely due to the average annual air temperature being less than the pivot point of 11 °C.

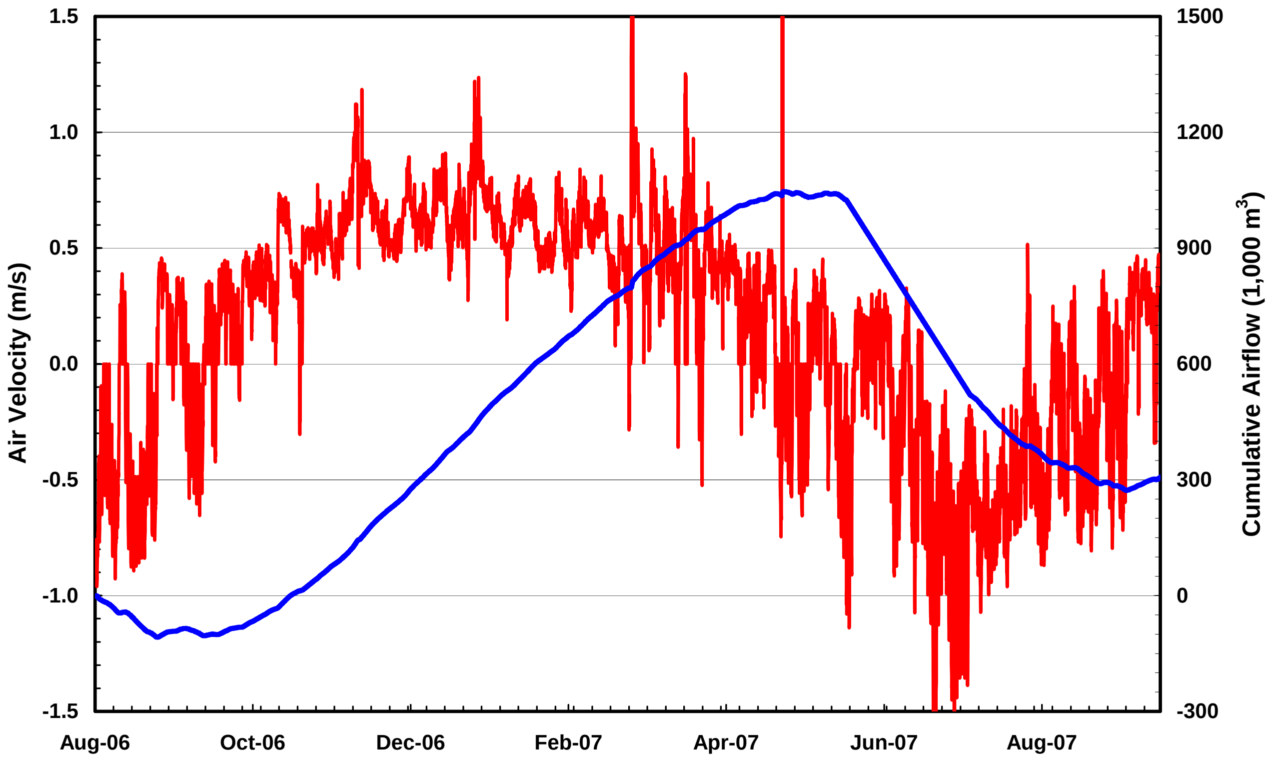

Fig. 11. Air velocity and cumulative air flow (blue). Periods of air velocity data loss, totaling less than eight weeks, are estimated using the relationship in Figure 9.

One incident of pressure-controlled respiration was recorded on March 12, 2007 for approximately six hours during the spring melt. The till cover was unfrozen through the winter of 2006-2007 due to a large and early insulating snow pack; the melting snow through the winter kept the cover near saturation. Producing the pressure-controlled event required additional moisture from snowmelt during 7 °C air temperature and a rain storm of 12 mm.

4.2 Phase 2 Internal Data

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 lead and the zinc in the Sullivan ore occur as sulfides and there are also abundant iron sulfide minerals. 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 (see Figure 12). 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.

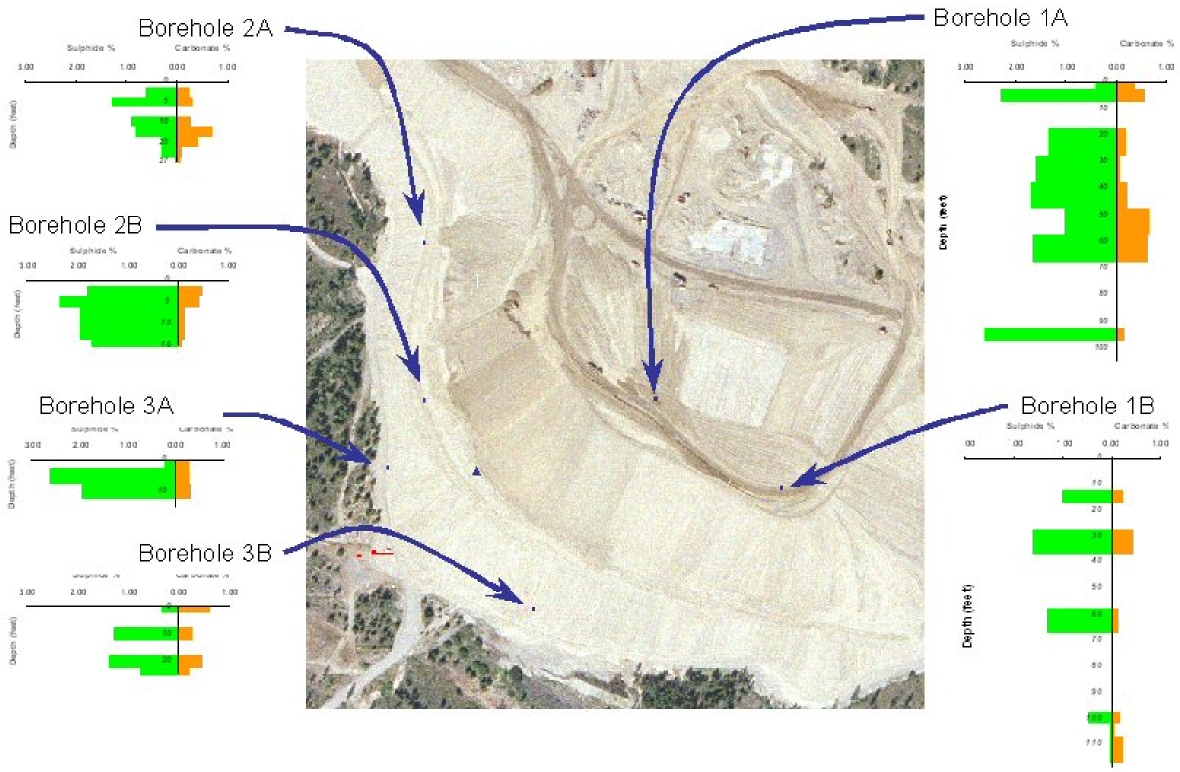

Fig. 12. Sulfide (left) and carbonate (right) content measured in drillhole samples (% S and % CO_3 by weight).

The presence of sulfides and carbonates indicates a potential for the rock to both consume oxygen and produce carbon dioxide. Analyses of air samples taken from within the dump confirm that this is occurring (see Figure 13). 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 drillhole. These results conclusively demonstrate that air within the dump is reacting with sulfide minerals, leading to the depletion of oxygen and enrichment of carbon dioxide.

The instruments within the No. 1 Shaft Waste Dump show that internal temperatures range from about 5 °C to about 16 °C. The temperatures vary from one location within the dump to another (see Figure 14). The higher temperatures are generally found at the greater depths near the middle of the dump, and the lowest temperatures are found near the dump surface and at the base where the dump material meets natural ground. At any one location, however, the temperatures are very nearly constant, i.e. they do not change much over time.

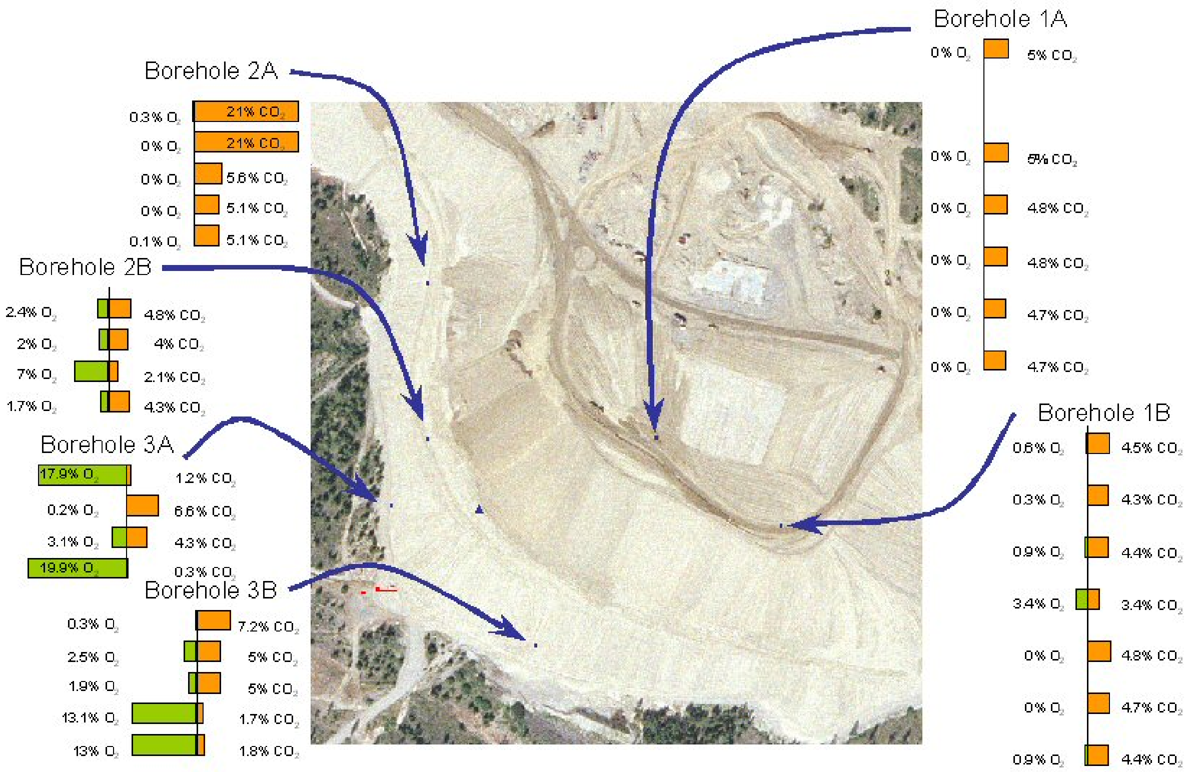

Fig. 13. Borehole oxygen and carbon dioxide at depth (June 7, 2007)

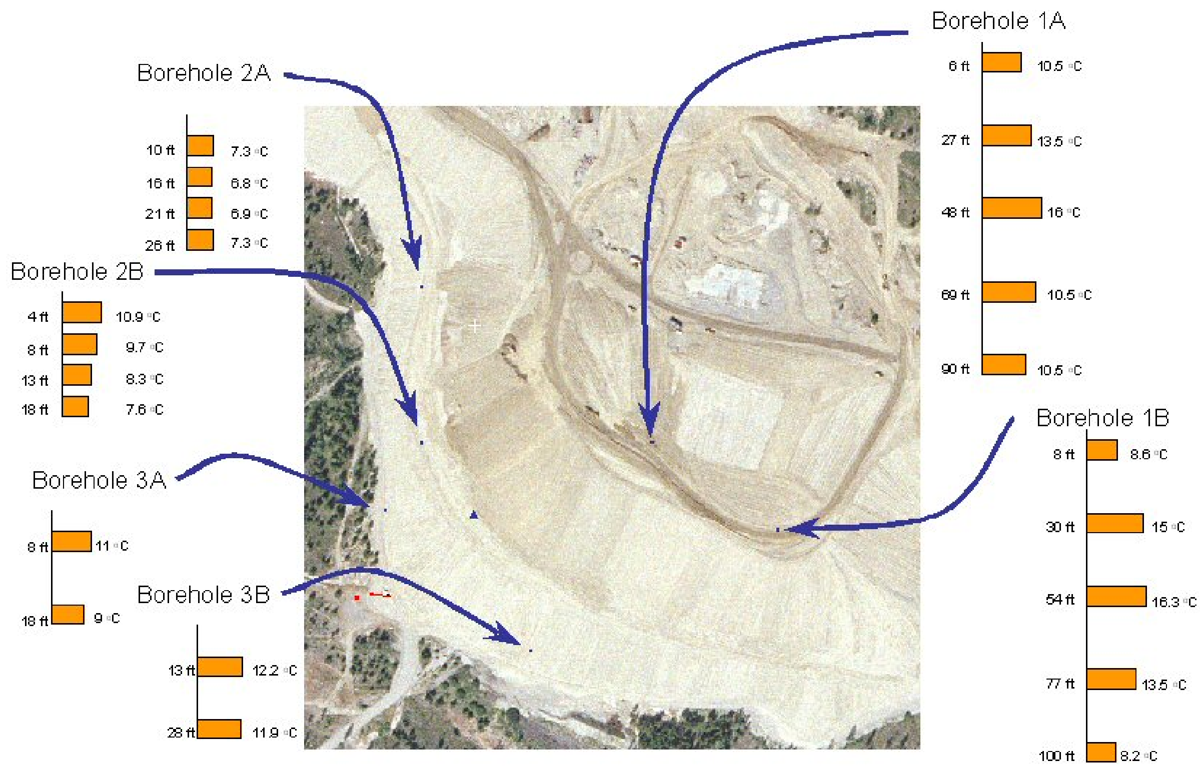

Fig. 14. Borehole temperatures at depth (May 31, 2007)

Air temperatures in the area cover a much broader range. During the period in which the internal dump data were collected, outside air temperatures ranged from -7 °C to +26 °C. Comparing that range to the range of internal temperatures shows that there is a clear potential for temperature driven air flow. There are periods when the surrounding air is much cooler than that in the dump, leading to a tendency for the air to rise upward and out of the dump surface. There are other periods when the air within the dump is cooler than the surrounding air, leading to air movement downward and out of the dump toe.

The potential for barometric pressure to drive air flow is less clear from the internal dump data. Measurements of air pressures within the dump show that they consistently follow changes in the atmospheric pressure. The rapid response to barometric pressure changes indicates that the dump is not a sealed system. Barometric pressure effects therefore appear to be much less likely than temperature effects to drive sustained air flows.

Changes in air composition can also cause air movement in waste rock piles. For example, oxygen is one of the heavier components of air, so when it is depleted by sulfide oxidation reactions, the air becomes less dense or lighter. Since both processes are occurring within the No. 1 Shaft Waste Dump, it is possible that changes in gas composition could affect gas flow. The ranges of oxygen and carbon dioxide concentrations measured to date indicate that most of the dump air is, on average, slightly lighter than the surrounding air, with all but three locations being lighter than air by 0.6% or less (see Figure 15). However, the differences are unlikely to be sufficient to cause a sustained flow of air throughout the dump as a whole.

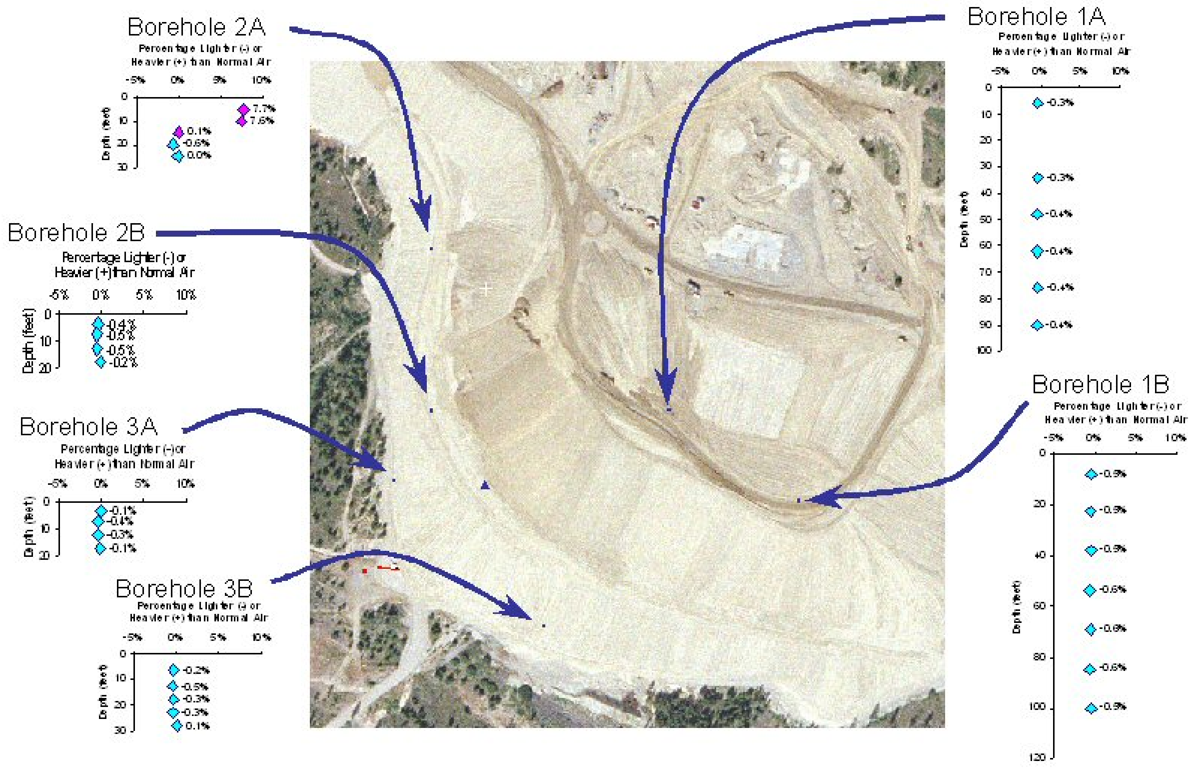

Fig. 15. Differences in air density resulting from oxygen depletion and carbon dioxide production

It can be concluded that the dominant cause of air movement within the No. 1 Shaft Waste Dump is the differences between air temperatures within and outside of the dump. Barometric pressure and gas composition effects may cause localized or short term air movements, but are much less important than temperature in driving overall air flows.

5. CONCLUSIONS

In response to four fatalities at the Sullivan Mine No. 1 Shaft Waste Dump, an investigation was begun to understand the processes that resulted in low-oxygen, high carbon dioxide gas to enter the monitoring station. With a pivot point of approximately 11 °C, air temperature is observed to be the dominant respiration control, which was also likely true in May 2006. Chemical laboratory analysis of drill cuttings has shown carbonate minerals present in both the till cover and the sulfidic waste material. 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.

Several specific questions that have occurred to the Technical Panel relate to how combinations of fundamental processes with site-specific conditions can enhance risks. For example, is the combination of temperature and sulfide minerals alone enough to create risks, or are the other elements present at the No. 1 Shaft Waste Dump, such as the toe drain, the cover, the 400 mm pipe and the enclosed station, necessary factors? Only a more detailed review of the monitoring data and a careful extrapolation to other sites will answer those questions.

In the interim while data continues to be gathered and assessed, the Technical Panel believes that all individuals responsible for safety on mine sites should be aware of the hazards associated with waste dump air, and that the risks should be stated as broadly as possible. Based on the findings to date, the presence of any of the following should be considered to significantly raise the risk level:

- Sulfide minerals in waste rock, which can deplete oxygen from air;
- Any combination of sulfide minerals and carbonate minerals, which can lead to production of carbon dioxide;
- Air temperatures that are higher than temperatures within waste dumps, which can lead to temperature driven outflows of dump air;
- Sharp drops in barometric pressure, which can lead to pressure driven outflows of dump air;
- Any factors that serve to concentrate or confine dump air outflows, including soil covers, toe drains, and water sampling pipes, but also including coarse rock channels formed naturally during dumping, finer rock layers formed by traffic or re-grading, and localized excavations into the dump toe;
- Any factors that serve to limit the mixing of out-flowing gases with the surrounding air, including monitoring stations but also any other walls or berms, heavy vegetation, and local ground depressions, as well as barometric inversions or similar weather conditions that cause pockets of air to accumulate in depressions.

Although the above risk factors are stated in terms of waste rock dumps, some of them may also be present in tailings dams, tailings piles, ore stockpiles, and other site components. At this time the Technical Panel is not limiting possible affected areas to those confined by a structure. It is possible that open areas, such as a low-lying area on a calm day or a sheltered ravine at a dump toe, could harbour impacted gas that pose a risk. The Technical Panel recommends that mine sites conduct risk assessments of site components where these factors may be present and use the findings to develop safe work procedures.

6. ACKNOWLEDGEMENTS

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