Diavik Waste Rock Project: Wind-Induced Gas Transport

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Abstract
The availability of oxygen and the thermal state of a waste-rock pile are controlled by gas transport processes, including concentration-gradient driven diffusion, thermally-driven convection and wind-driven advection. At the Diavik Diamond Mine, differential gas pressures are measured at 1 minute intervals at 49 locations within a 15 m high test pile (which contains 0.053 ± 0.035 wt. %S), and at 14 locations on the surface of the test pile. Wind speed and direction are measured at 10 minute intervals. The data indicate that the pressure responses at sampling points within and on the surface of the test pile are well correlated to wind vectors. The strength of the correlation is highest for the dominant wind direction, and also the strength of the correlation is inversely proportional to the distance between measurement ports and the pile/atmospheric boundary; suggesting that wind-driven advection is the dominant gas transport processes in the test pile. The linear relationship between internal pressure measurements and surface pressure measurements indicates that gas flow within the test pile is laminar. The high rates of gas transport due to wind-driven advection contribute to high rates of oxygen and thermal transport.

Key Words:Waste rock, gas transport, permafrost, wind.

Introduction
The rate of sulfide-mineral oxidation and concentration of oxidation products in leach water from waste-rock piles is affected by coupled physical processes, including water flow, heat transport and gas transport (Figure 1). In particular, thermal and gas transport processes can be highly coupled. For example, where sulfide-oxidation rates are high, heat from sulfide oxidation can generate density driven convective air currents. These air currents can result in increased rates of oxygen transport, resulting in a positive feedback enhancing the rate of sulfide oxidation (Lefebvre et al., 2001a, b). The controlling processes and their coupling are determined by a number of factors, including sulfide-mineral content and surface area, waste-rock permeability and ambient conditions.

In permafrost regions, where the mean annual temperature is below0 °C, freezing of the waste rock has the potential to limit sulfide-oxidation rates and transport of leach water. In these environments, the extent of freezing, and the degree of thawing in the summer months, will depend on the mechanisms and rate of thermal transport into the piles. Possible thermal transport mechanisms include, 1) conductive transport driven by thermal gradients, 2) convective transport driven by air density gradients as a result of internal heat production and/or changes in ambient air temperatures, and 3) advective transport driven by pressure gradients at the boundaries of the piles, specifically due to wind flow over the piles.

At the Diavik Diamond Mine in Canada's Northwest Territories, three experimental-scale waste-rock piles (test piles) were constructed (Smith et al., 2009). Observations from the testpiles suggest that the annual freeze-thaw zone is deeper into the test pile than would be predicted considering only conductive and convective thermal transport, suggesting that wind-driven gas transport may also be influencing the thermal transport regime (Pham et al., 2009). Wind-driven gas advection will also enhance the rate of oxygen transport in the uncovered test piles, but the oxygen concentration within the test piles always remains near atmospheric, suggesting that oxygen-consumption rates are low compared to oxygen-transport rates (Amos et al., 2009a). One of the three test piles was fitted with a gas concentration and pressure monitoring system to determine the mechanisms of gas transport within the test pile (Amos et al., 2009b). This paper provides a review of gas transport research conducted at the Diavik site with a particular focus on the implications for thermal and oxygen transport.

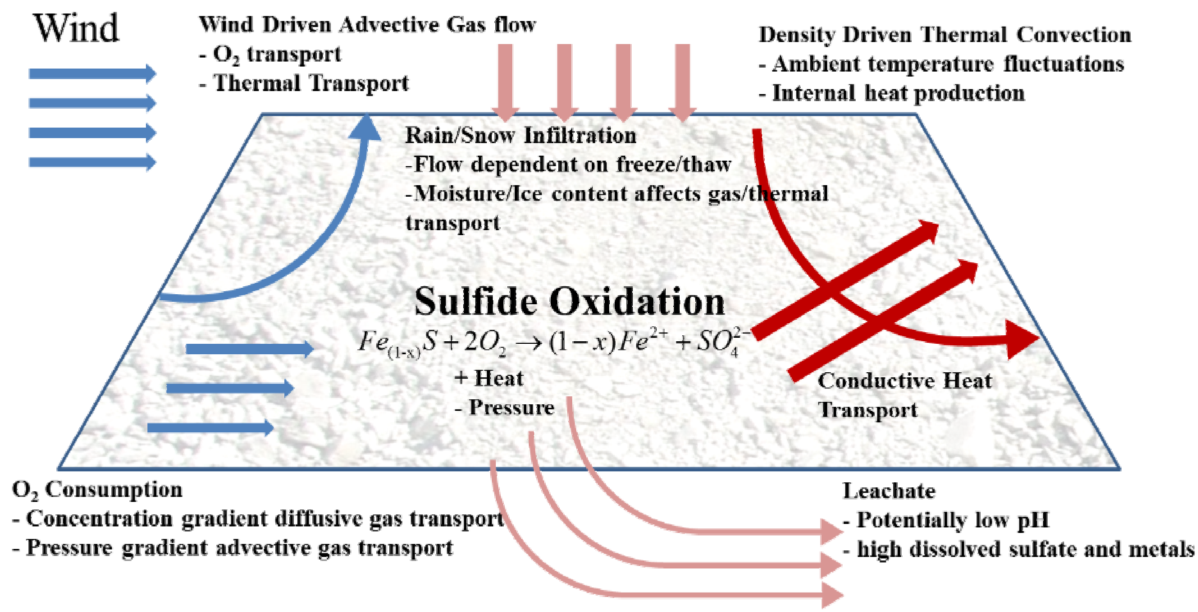

Figure 1. General conceptual model of coupled physical processes affecting sulfide oxidation rates in waste-rock piles. Modified after Lefebvre et al. (2001a).

Methods

At the Diavik Diamond Mine, three test piles were constructed using run of mine (ROM) rock and standard mining equipment. The Type III test pile, containing 0.053wt % sulfide, was fitted with instrumentation to measure spatial and temporal changes in oxygen and carbon dioxide concentrations within the test pile, and spatial and temporal changes in gas pressures on the surface of, and within the test pile (Smith et al., 2009).

Measurements of gas concentrations and pressure are obtained from 3.2 mm or 6.4 mm polypropylene (PP) tubes placed within the test pile during construction. Bundles of 15 tubes were prepared by stringing the (PP) tubes through 50 mm diameter flexible PVC conduit (Figure 2). PP tubes were terminated through holes drilled through the PVC conduit at intervals so that the final spacing of the sampling points would be at 1 m vertical intervals. Spray foam insulation was used to prevent air flow through the conduit (Amos et al., 2009b; Smith 2009).

During construction of the Type III test pile, prepared instrument lines, including the gas sampling lines, were placed along exposed tip faces of the test pile (Figure 3) then covered with ROM using an excavator to protect the lines as construction of the test pile continued (Figure 4). Instrument lines were placed on four separate tip faces at 20, 15, 10, and 5 mfrom the end of the test pile, faces 1 through 4, respectively. Gas sampling bundleswere installed on each face at 2.5 and 7.5 m offsets on either sideof the longitudinal center line (Figure 5, Smith 2009).

Figure 2. Preparation of instrumentation bundles for emplacement within the test piles.

Figure 3.Exposed internal face of the Type III test pile showing placement of instrumentation bundles, including gas lines.

Figure 4. Excavator covering instrumentation lines with protective ROM layer. Following protectionof the instruments, test pile construction continued with standard mining equipment.

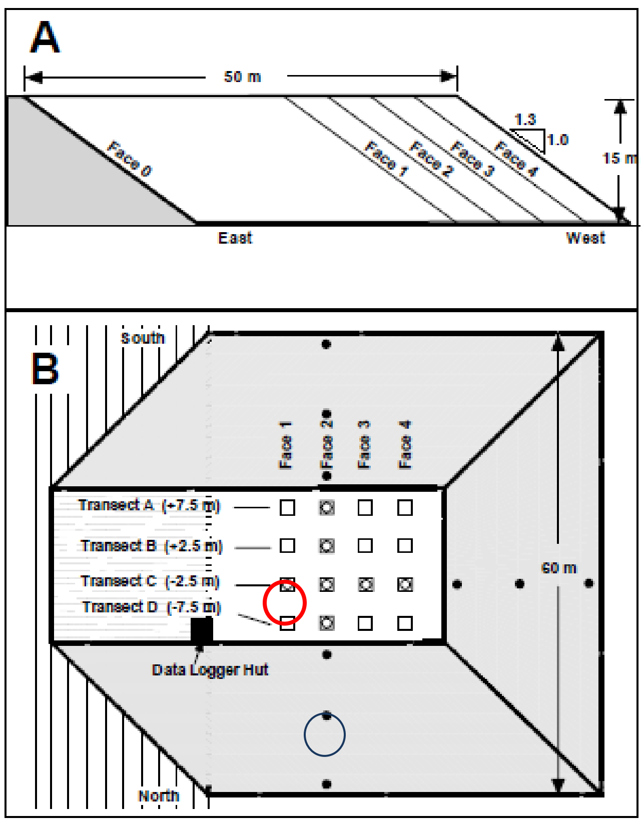

Figure 5. A) Schematic side view of the Type III test pile showing the location of the instrument faces. B) Schematic plan view representing the Type III test pile. Open squares represent the surface location of gas sampling bundles installed along the tip faces. Open circles represent the gas sampling bundles connected to the gas pressure datalogging system. Filled circles represent single pressure sampling locations on the surface of the test pile (Reproduced from Amos et al.,

2009b). Large red circle denotes sampling bundle 31N2. Large bluecircle denotes surface sampling point 3NS-7.

On the Type III test pile, an automated datalogging system was installed to measure gas pressures at 49 locations within and 14 locations around the test pile at one minute intervals (Amos et al., 2009a, b). The system consists of 7 differential pressure transducers (Modus Series T ±50 Pa, accuracy ±1 Pa) enclosed in small electrical service boxes (Figure 6A and B) located near 7 of the gas sampling bundles (Figure 5). Each pressure transducer is connected to 7 sampling locations within each bundle through a series of solenoid valves, allowing each sampling point to be measured independently. The transducers are located as close as possible to the sampling bundles to reduce the exposed tubing length and minimize noise. Differential pressure is measured between the sampling point and a reference point approximately 25 mm below the surface of the test pile at the location of the sampling bundle. An additional differential pressure sensor is located within an instrumentation hut on top of the test pile and records differential pressures between the surface sampling points and the reference point at face 2. Sample tubing is run from the instrumentation hut to the surface sampling locations through 50 mm PVC conduit and exposed at the ends through holes in the conduit. Exposed ends are covered with crushed rock to minimize wind effects on the tubing ends. Pressure data is recorded with a Campbell Scientific CR1000 datalogger at 1 minute intervals. In addition, wind speed and wind direction are recorded at 10 minute intervals using an RM Young Model 05305 wind monitor mounted approximately 7 m above the Type III test pile(Figure 6C). Data collected is transmitted through a radio telemetry system to an on-site base station, and then transmitted via an ftp server to university researchers.

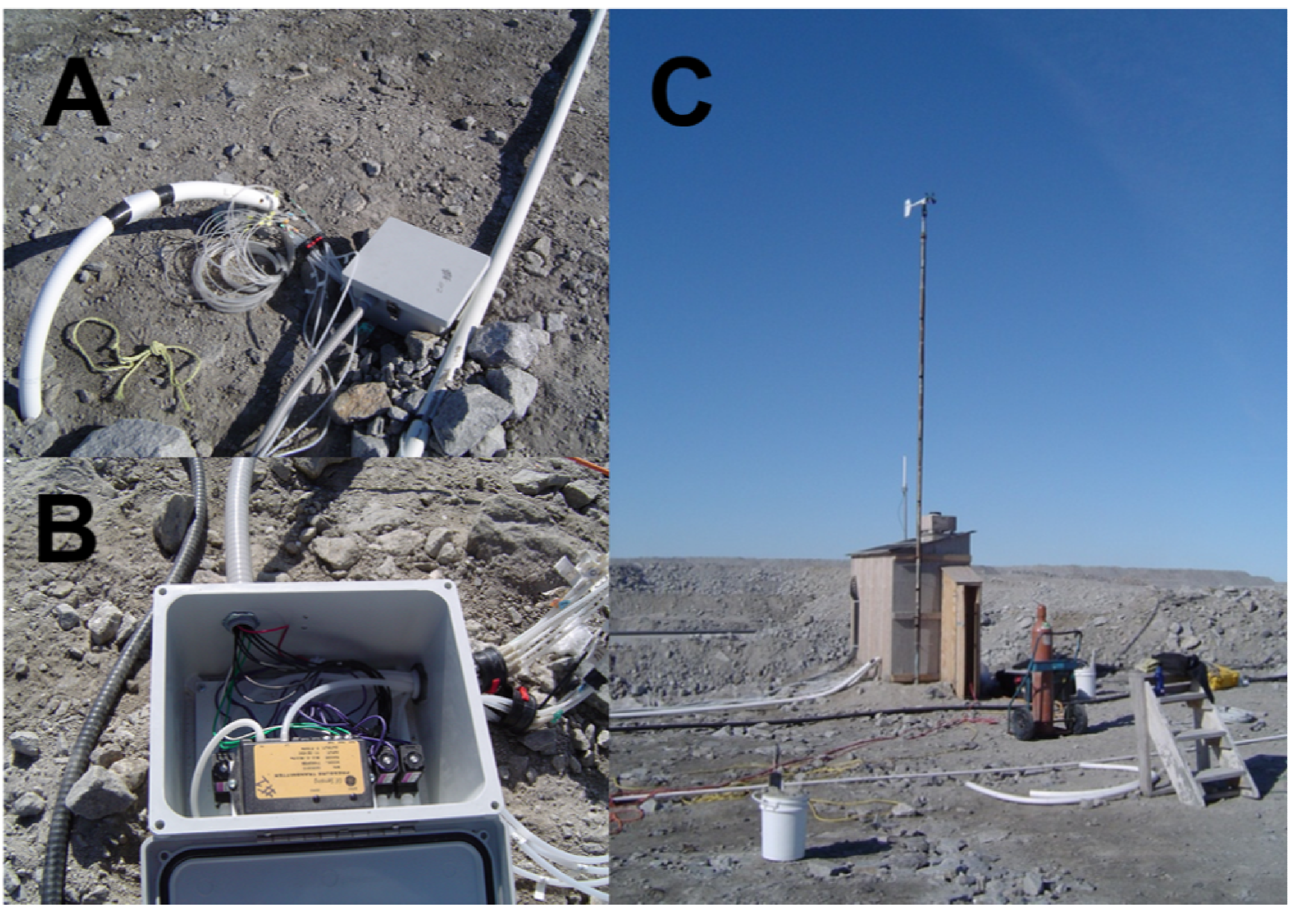

Figure 6.A) Gas pressure sampling box connected to a gas sampling bundle on the Type III test

pile. B) Interior of pressure sampling box showing the differential pressure transmitter and solenoid valves. C) Wind monitor installed on Type III test pile.

Results and Discussion

Wind induced gas transport

Differential pressures measured within the Type III test pile respond to ambient wind conditions. Figure 7 shows 2-dimensional contours of differential pressure along the north-south and east-west sampling transects with the wind blowing from the south at approximately 20 km h^{-1}. Pressure gradients develop around the surface of the test pile resulting in the development of pressure gradients through the interior of the test pile. With the wind from the south the highest internal pressures are observed on the southern side of the test pile.

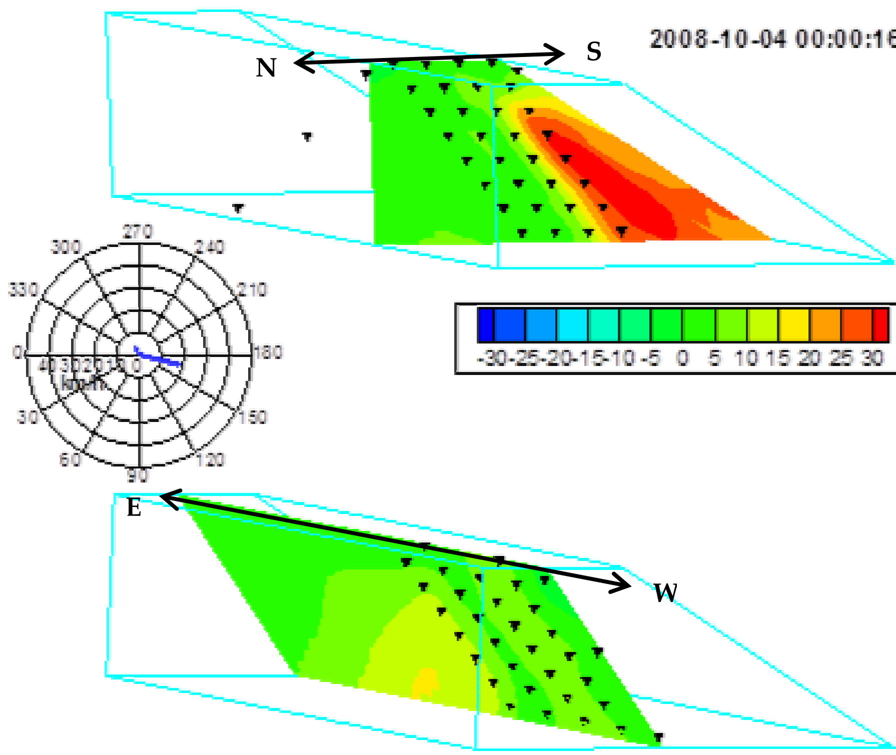

Figure 7.2-D spatial profiles of differential pressure (Pa) within the Type III test pile along with the prevailing wind conditions on October 4, 2008 at midnight. 2-D contours are obtained from 3-D kriging of all available data points. 2-D profiles shown are along North-South (upper) East-West (lower) sampling transects (indicated by the black arrows). Blue line represents the 3-D outline of the test pile. Triangles on the contour plots represent measured data points spaced 2 m vertically. Radial diagrams show wind direction in degrees plus wind speed along the radius in km/h (0 indicates North, 90 indicates East, 180 indicates South, and 270 indicates West).

The magnitude of the pressure gradients observed within the test pile is a function of both the wind speed and wind direction. Figure 8 shows 2-dimensional contours of differential pressure along the north-south and east-west sampling transects with the wind blowing from the southeast at approximately 30 km per hour. Although the wind speed is significant, the differential pressures measured within the test pile are small, i.e. less than 5 Pa. The lack of pressure response within the test pile on this occasion is due to the geometry of the test pile. The test pile was built from a ramp on the east side so that the east side of the test pile is not exposed to the wind. As a result, wind from the east does not create pressure gradients around the test pile.

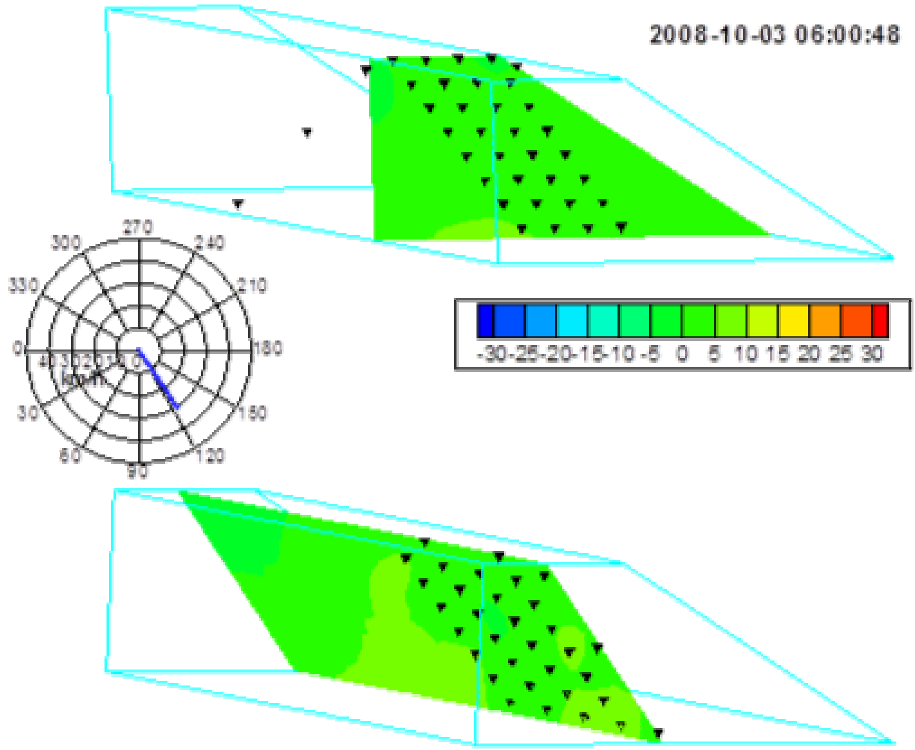

Figure 8. 2-D spatial profiles of differential pressure (Pa) within the Type III test pile along with the prevailing wind conditions on October 3, 2008 at 6:00 am. 2-D contours are obtained from 3-D kriging of all available data points. 2-D profiles shown are along North-South (upper) East-West (lower) sampling transects. Blue line represents the 3-D outline of the test pile. Triangles on the contour plots represent measured data points spaced 2 m vertically. Radial diagrams show wind direction in degrees plus wind speed along the radius in km/h. Refer to Figure 7 for transect orientation.

Internal pressures measured within the Type III test pile show a strong correlation to wind vectors measured on top of the test pile (Figure 9). Correlations are generally stronger for the north and south wind vectors due to the predominance and strength of north and south winds (Chi, 2011). In addition, correlations are strongest for sampling points closest to the windward side of the test pile. Note that correlation between internal pressure measurements and wind vectors is somewhat non-linear, as would be expected due to turbulent effects created at high wind speeds. However, due to the variability in the data non-linear regressions did not provide better fits to the data. Correlations between pressures measured on the surface of the test pile and internal pressures show a more linear trend (Figure 9) indicating laminar flow within the test pile (Chi, 2011).

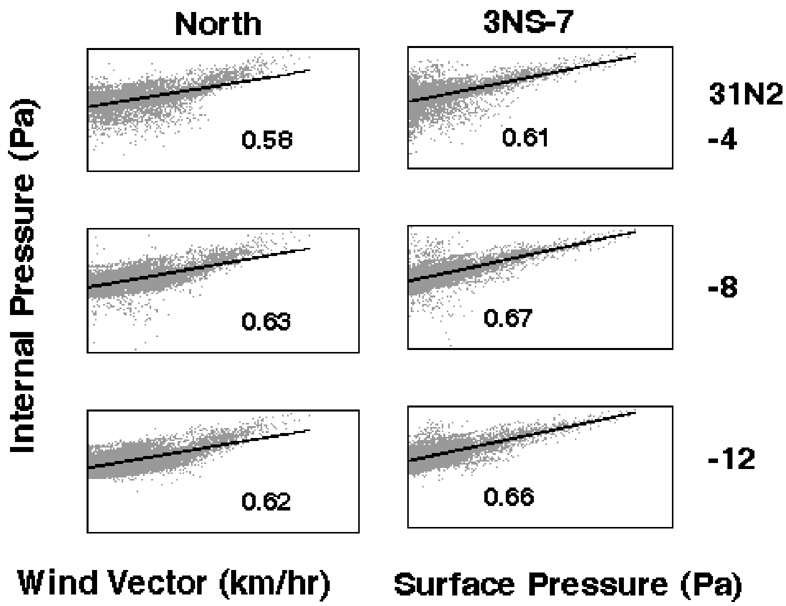

Figure 9. Correlation of pressures measured at sampling points 31N2-4, -8 and -12 with the north wind vector and external sampling point 3NS-7. Sampling bundle 31N2 is on the Type III test pile, Face 1, north offset 2.5 m (see Figure 5), -4, 8 and 12 refer to depth below the upper surface of the test pile. External sampling point 3NS-7 is on the north slope of the Type III test pile, 7 m vertically from the upper surface of the test pile.

Implications for oxygen and thermaltransport

Gas transport processes can include diffusion due to concentration gradients, convection due to thermally driven air density gradients, and advection due to pressure gradients. Within the Type III test pile no gas concentration gradients are observed so diffusion is not a significant transport mechanism. Thermal measurements indicate that the oxidation of sulfide minerals within the test pile does not result in a significant amount of heat generation, so that heat generated within the test pile will not result in thermal gradients sufficient to drive convective currents. Changes in ambient temperatures on a seasonal time-scale will result in air density gradients between the interior and exterior of the test pile. These gradients are expected to be sufficient to drive gas transport, although due to the small size and high permeability of the test pile these gradients are not readily observable in the measured pressure data.

Measured pressures within the Type III test pile show a clear response to the influence of wind, suggesting that wind-induced gas transport is a significant gas transport mechanism within the test pile. The rate of wind-induced gas transport will be dependent on the pressure gradients that develop externally to the test pile and also the air permeability of the test pile.*In situ*measurements of air permeability using air permeability balls installed within the Type III test pile average 2×10^{-9} m^2, which is on the high end of permeability measured in waste rock piles in general (Ritchie et al., 1994). Together, the wind-induced pressure gradients and the high permeability of the Type III test pile have the potential to result in high rates of gas transport.

In waste rock, the oxidation of sulfide minerals can be dependent on the availability of oxygen. Measurements of oxygen concentrations within uncovered test piles at the Diavik site show no indication of depletion of oxygen throughout (Amos et al., 2009a). Measurements are taken throughout the year, and no temporal changes in oxygen concentrations are observed. Oxygen concentration profiles within waste rock are dependent on the rate of oxygen supply controlled by gas transport processes, and the rate of oxygen consumption through sulfide oxidation. Sulfide content in Diavik waste rock is relatively low; the

Type III test pile has a sulfide content of 0.053wt % S. As a result the rate of oxygen consumption by sulfide oxidation is expected to be relatively low. Balanced with the high rate of gas transport due to the influence of the wind, oxygen concentrations remain near atmospheric levels throughout the test pile.

Monthly average temperatures at the Diavik site range from a high of 12 °C in July to a low of -30 °C in January and February (Pham 2009). Thermal mass carried by gas into and out of waste rock will influence the temperatures within the piles. In the Type III test pile temperatures fall to below -10 °C throughout the entire test pile in the winter. In the summer months, temperatures throughout the test pile rise to above 0 °C (Pham et al., 2009). These drastic fluctuations in internal temperature are much greater than was initially predicted considering only conductive and convective thermal transport, suggesting that wind-driven gas transport is affecting the thermal regime within the test pile.

Conclusions

The mechanism of thermal and gas transport processes, and the coupling of these processes, is dependent on a number of factors including the ambient conditions and the properties of the waste rock pile. In the Type III test pile at the Diavik site, the relatively high permeability and ambient wind conditions result in wind-induced advective gas transport through the test pile. Combined with the large fluctuations in ambient temperatures, the advective gas transport results in annual freezing and thawing through most of the full thickness of the test pile.

Ongoing research will quantify the rates of gas, oxygen and thermal transport in the Type III test-pile due to wind-induced pressure gradients. This research will be carried out through the development and application of numerical models that take into account the transient nature of wind speed and wind direction, and coupling to thermal and geochemical processes. This modelling will be used to determine the significance of wind-induced gas transport in comparison to other mechanisms of gas transport and thermal transport.

Acknowledgements

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