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Monitoring of the geochemical evolution of waste rock facilities at Newmont's Phoenix Mine

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Abstract

Newmont Mining Corporation's Phoenix Mine in Nevada, USA is actively reclaiming historic and current waste rock disposal areas with evapotranspiration (ET) covers to reduce the long-term risk of acid rock drainage. The waste rock is typically sulphide enriched and considered to be potentially acid generating (PAG). The total sulphide content of all waste material averages 2–3%, of which less than 20% is pyrrhotite with the remaining being a combination of pyrite and marcasite. There are pockets (often in the hundreds of tons range) of material that average greater than 50% sulphide.

ET covers consist of nominal 2 m thick alluvial soil and/or non-PAG waste rock placed over the waste rock material. To monitor the ET cover's capacity to store and release incident precipitation and the evolution of potential acid rock drainage generation in closed waste rock facilities, near surface (less than 3.5 m below ground surface) cover performance monitoring sensor nests and deeper subsurface geochemical evolution monitoring wells (to a maximum depth of 67 m) have been installed in the South Iron Canyon and North Fortitude rock disposal areas. Near-surface sensor nests and the geochemical evolution monitoring wells are instrumented at various depths with water content, water pressure potential, air pressure, oxygen concentration, temperature, and water flux sensors. These monitoring systems provide information on net percolation in the waste rock, air flow within the waste rock, and the relative oxidation of sulphide material at depth. In addition, the instrumentation has been designed to test hypotheses regarding the distribution and movement of water and air in "end dumped" lifts.

Initial data indicates that the cover systems are effectively storing and releasing precipitation. Deep zones of elevated temperature within the waste rock have been identified and may indicate the presence of sulphide enriched waste rock being exposed to incident precipitation for prolonged periods during the disposal area construction phase. Three years of monitoring data will be presented to illustrate cover system performance and controlling factors in the geochemical evolution of the waste rock disposal areas.

1 Introduction

The Newmont Mining Corporation, Phoenix Mine (Phoenix) is located in the Great Basin region of the United States, about 16 km south of the community of Battle Mountain in the state of Nevada. Phoenix began operation in 2005 after Newmont Mining Corporation gained ownership of the historic property with the 2001 purchase of Battle Mountain Gold. Mining at Phoenix is accomplished through conventional open pit methods. Waste rock generated by existing operations is disposed either as pit backfill material or in end dumped constructed waste rock facilities. Waste rock at Phoenix is typically sulphide enriched and considered to be potentially acid generating (PAG). The total sulphide content of all waste material averages 2–3%, of which less than 20% is pyrrhotite with the remaining being a combination of pyrite and minor amounts of marcasite. Pockets of sulphide rich material, often in the hundreds of tons range, are encountered that average greater than 50% sulphide.

Phoenix is actively reclaiming historic and current waste rock facilities with evapotranspiration (ET) covers designed to minimise meteoric water infiltration and promote vegetative growth. The capacity of the installed ET covers to store and release incident precipitation and limit the downward percolation flux of precipitation below the zone of ET are monitored by Phoenix. ET cover monitoring and monitoring of the evolution of potential acid rock drainage generation at two closed waste rock facilities, South Iron Canyon (SIC) and North Fortitude (NF), are the subject of this paper.

2 Cover system performance monitoring

2.1 Site conditions

The elevations of the waste rock facilities range between 2,085 and 1,785 m at SIC and 2,035 and 1,920 m at NF. The climate at the site is semi-arid characterised by dry summers and cold winters. Average annual precipitation at Battle Mountain (elevation 1,385 m) from 1944 through 2010 is 207 mm, with most precipitation received in December through May.

Precipitation data is collected on a site near SIC at an elevation of approximately 2,000 m. The reference crop ET from a well-watered grass (ETo) was calculated using the modified Blaney-Criddle method (Zhan and Shelp, 2009). The recorded average annual precipitation during the 2008 to 2010 monitoring period was approximately 232 mm; estimated ETo was approximately 1,787 mm per year (Figure 1). Estimated ETo exceeds average annual precipitation by approximately 1,500 mm per year.

The ET cover at SIC consists of non-PAG waste rock at the toe, grading to alluvium at mid-slope, and predominately non-PAG waste rock on the top-slope. The ET cover at NF consists of mixed non-PAG waste rock and alluvial material. Measured ET cover thickness at SIC and NF average approximately 2 m.

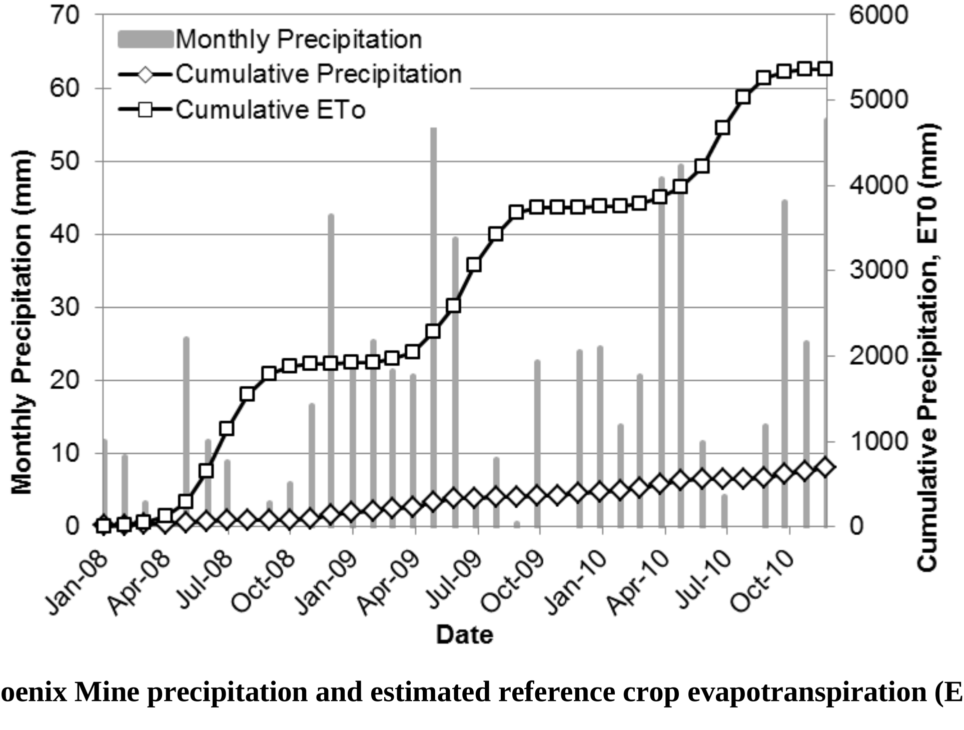

Figure 1 Phoenix Mine precipitation and estimated reference crop evapotranspiration (ETo)

2.2 Monitoring system

The ET cover monitoring system was installed to evaluate long-term cover performance at three different topographic locations at SIC (upper-, mid-, and toe-slope) and at two different topographic locations at NF (upper- and toe-slope). Monitoring system sensor types included soil water potential sensors (heat dissipation or HDS, and advanced tensiometers, or AT); soil moisture content sensors (ECH_2O); and water flux metres (WFM). Sensors were installed in the cover material and waste rock, to a maximum depth of approximately 3.5 m below ground surface (Figure 2). Soil water potential (HDS and AT) and water content (ECH_2O) sensors monitor the wetness of the soil cover and the removal of water through drainage and ET. Water flux metre (WFM) measurements provide a small-scale point measurement of deep flux at each location.

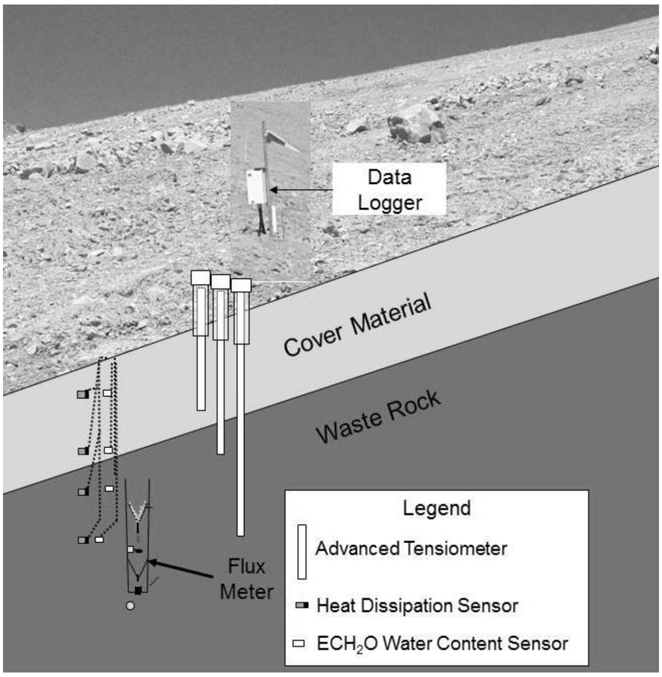

Figure 2 Cross-section of monitoring nest installation

Adjacent to the upper-slope ET cover monitoring systems are geochemical evolution monitoring wells instrumented with soil water potential sensors (HDS); soil moisture content sensors (ECH_2O); air piezometers; oxygen content sensors; and temperature sensors (Table 1; Figure 3). The oxygen content and temperature sensors provide an indication of oxygen consumption and heat generation resulting from oxidation of sulphide minerals. Air piezometers allow for measurement of air pressure gradients and direction and magnitude of air flow within the waste rock. The geochemical evolution monitoring wells were installed using dual rotary drilling with compressed air as the drilling fluid to a depth of 36.6 m below ground surface (bgs) at the SIC well and over the entire depth of the NF well. Water was used as the drilling fluid at SIC at depths greater than 36.6 m bgs.

Table 1 South Iron Canyon and North Fortitude monitoring systems and geochemical evolution monitoring well installation date and monitoring period

Facility	Station	Installation Date	Monitoring Period
South Iron Canyon	Toe-slope cover monitoring system	November 2007	14/11/2007 – 20/04/2011
	Mid-slope cover monitoring system	June 2008	04/06/2008 – 20/04/2011
	Upper-slope cover monitoring system (a)	May 2011	–
	Geochemical monitoring well (b)	September 2010	25/09/2010 – 22/03/2011
North Fortitude	Toe-Slope cover monitoring system	July 2010	15/07/2010 – 22/03/2011
	Upper-slope cover monitoring system	July 2010	15/07/2010 – 22/03/2011
	Geochemical monitoring well (b)	September 2010	15/09/2010 – 22/03/2011

(a) Monitoring station installed near date of publication.

(b) Monitoring wells located adjacent to upper-slope cover monitoring stations.

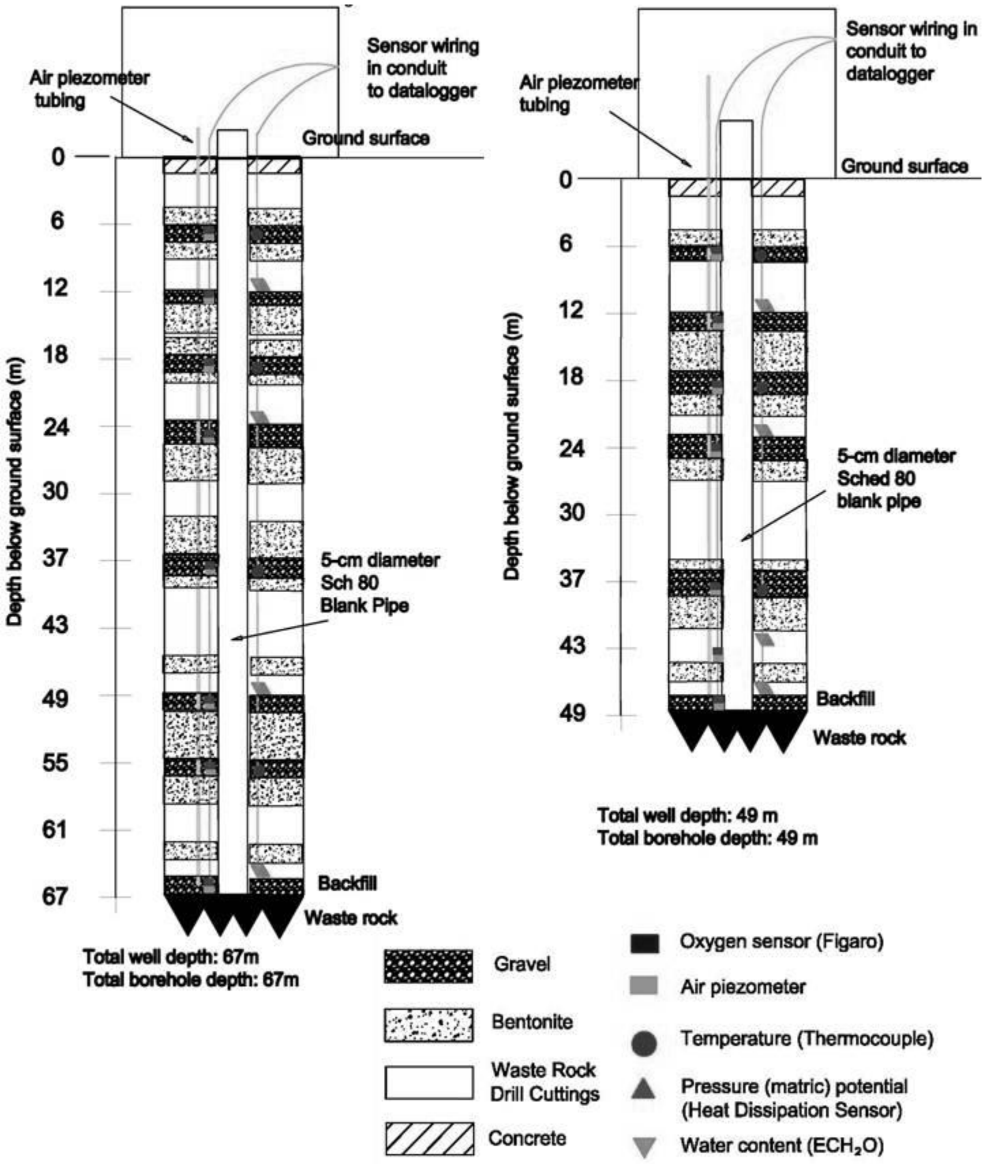

Figure 3 **As-built sensor schematic for South Iron Canyon (left) and North Fortitude (right) geochemical evolution monitoring wells**

3 Data and results

3.1 Conceptual model of cover system performance

The monolayer ET cover system design relies on a finer textured cover material overlying the coarser waste rock material acting as a medium in which moisture is stored until the processes of evaporation and transpiration recycle any excess water back to the atmosphere. Monolayer ET cover effectiveness in arid and semi-arid regions are well documented (Dwyer, 2003; Albright et al., 2004; Milczarek et al., 2009).

Wetting in the cover due to precipitation in the winter and spring is observed in the uppermost cover sensors and then the lower sensors as the wetting front advances. Variations in this sequence of progressive wetting, ,i.e. if a deeper sensor shows wetting prior to overlying shallower sensors may be caused by preferential flow or lateral movement of water. Drying of the cover is observed during the summer and fall as evaporation and plant transpiration increase.

3.2 South Iron Canyon

Measured water content at South Iron Canyon toe-slope (SICT) station rapidly increased in the soil cover and upper waste rock materials in response to infiltration of winter and early spring precipitation (i.e. rainfall and snowmelt) (Figure 4). There was also a slight increase in water content in late spring, lasting to mid-summer, in response to later spring precipitation events and slow drying trends (decrease in water content) in late summer and early fall. As expected, the shallowest water content sensor (at 30 cm bgs) responded most quickly to infiltration of winter precipitation (Figure 4). Measured water content at South Iron Canyon mid-slope (SICM) produced similar trends to that observed at SICT. Soil water potential data also show rapid changes in soil water potential in response to infiltration of winter precipitation at SICT and SICM and the same slow drying trend observed in water content data in later summer, fall, and in early winter (data not shown). The South Iron Canyon upper-slope (SICU) station was installed near the time of publication and data for this station is not presented.

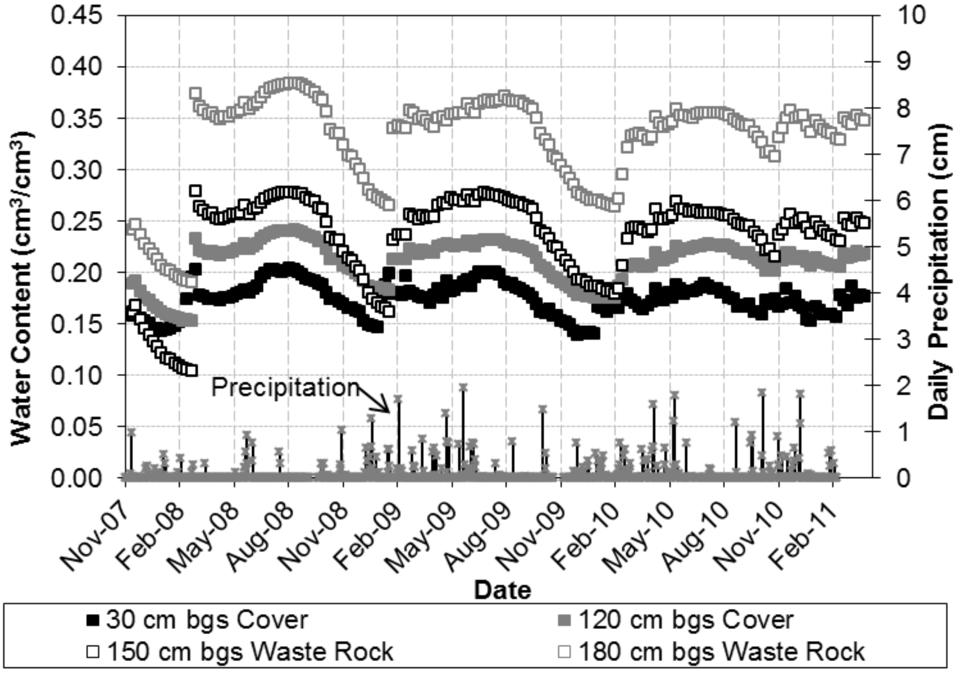

Figure 4 Water content and precipitation at SICT

Temperatures in the soil cover and the upper region of underlying waste rock at the SICT are generally similar to air temperatures, being slightly warmer in the winter and slightly cooler in the summer (Figure 5). In contrast, relatively higher soil than air temperatures are observed at SICM, and the temperatures become higher with depth. The warmer temperatures at SICM indicate that sulphide oxidation is occurring and generating heat in the process.

Temperatures exceeding 40°C were observed at 18.9 to 55.5 m bgs at the SIC geochemical borehole and indicate that sulphide oxidation was occurring (Figure 6). Warm conditions over this depth interval were also observed during drilling. Temperatures at 37.2 m bgs exceeded 75°C, eventually resulting in sensor failure at this depth. The deepest sensor depth of 65.4 m bgs coincides with the top of the historic Battle Mountain Gold waste rock facility and was cooler than all but the 6.7 m bgs sensor. Elevated temperatures, relative to the other sensor depths, at 37.2 and 47.7 m bgs also coincided with the addition of water during drilling which likely contributed to greater pyrite oxidation over this interval. The presence of wetter conditions at the depth of wet drilling was also observed by the water content and HDS sensors (data not shown). Overtime, the added water is expected to evaporate or be consumed by the oxidation reaction and return to pre-drilling conditions.

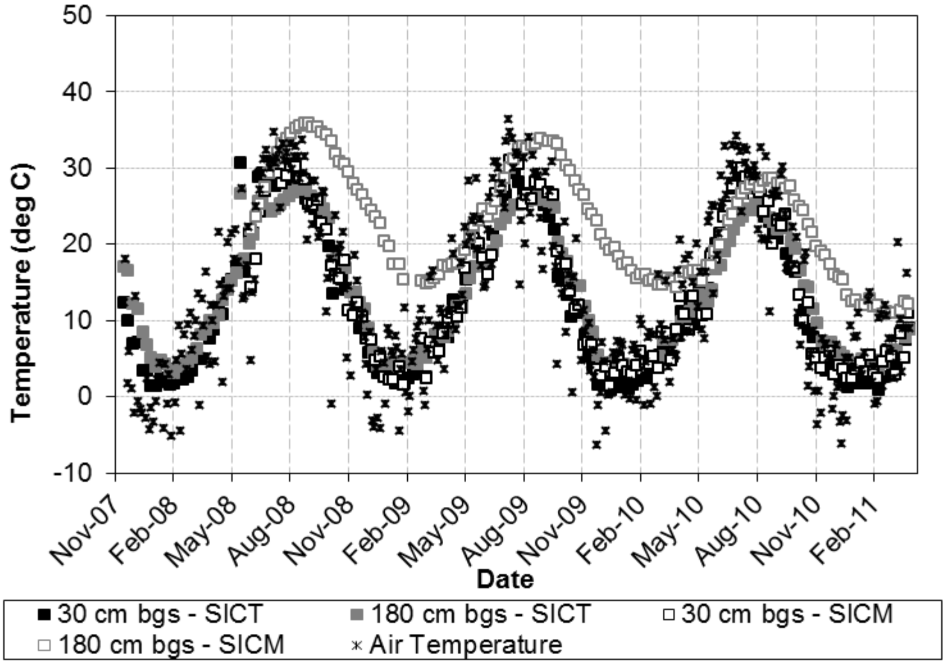

Figure 5 Air and soil temperature at SICT and SICM

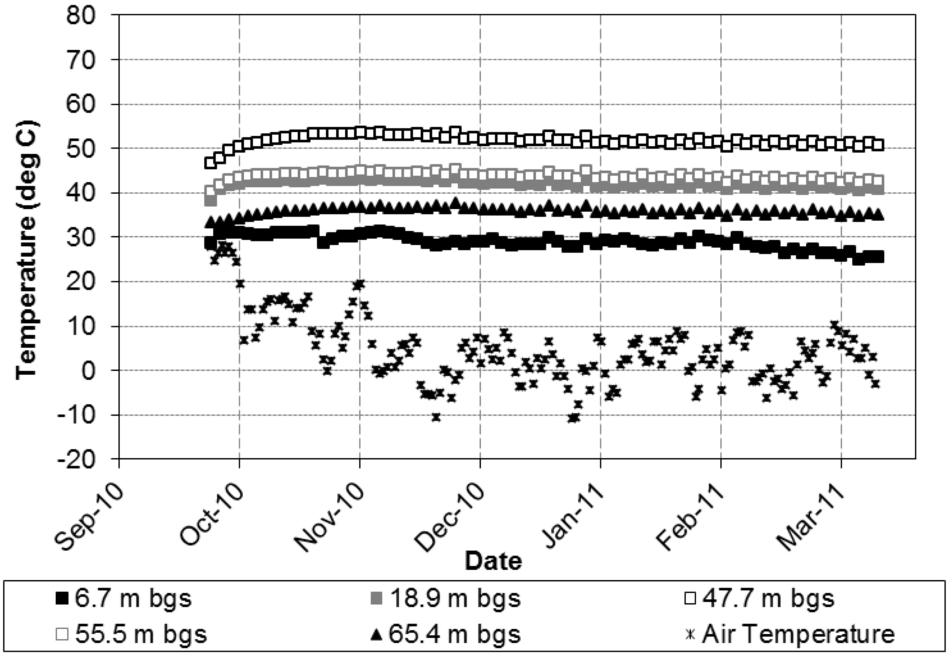

Figure 6 SICU geochemical borehole air and soil temperature

Deep waste rock oxygen contents are less than atmospheric (20.8%), indicating oxidation reactions may be occurring (Figure 7). Excluding the 6.7 m bgs sensor, oxygen contents remain relatively stable. The low oxygen content at 6.7 m bgs may represent lack of oxygen transfer immediately below the cover. Continued monitoring of oxygen contents, temperature, and water content will allow for estimation of oxidation rates over time. Vertical air pressure gradients within the waste rock are also being analysed to evaluate whether air flow within the waste rock is replenishing oxygen and controlling the geochemical evolution of the waste rock, similar to what has been observed at other properties (Lefebvre et al., 2001; Milczarek at al., 2009; Wels et al., 2003).

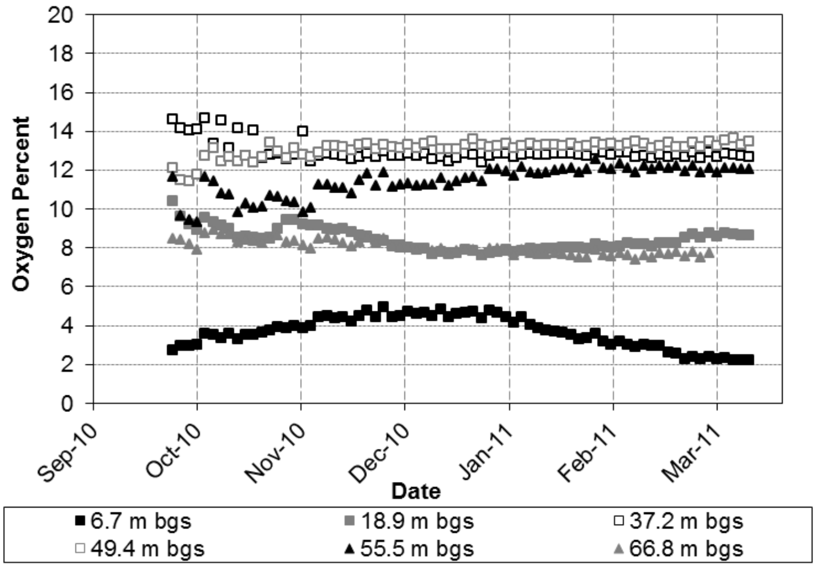

Figure 7 SICU geochemical borehole oxygen content

Total captured (cumulative) flux by the SICT WFM was noticeably higher (8.3 cm) than total captured flux by the SICM WFM (4.7 cm) (Table 2). These cumulative fluxes as a percentage of precipitation for SICT and SICM equal 14 and 8%, respectively. WFM data are missing from both SICT and SICM between 3 June 2008 and 31 March 2009, thus WFM measured flux are reported for the same time period of 1 April 2009 to 20 April 2011. SICT and SICM flux values represent unestablished vegetation conditions with less than a year of vegetation growth having occurred.

Differences between SICT and SICM flux values may be, in part, due to down-slope water flow converging at the SICT location. Additionally, the cover at SICT is non-PAG waste rock that is coarser than the alluvium cover at SICM and provides less water storage capacity than does the alluvium cover material. Regardless of these differences in WFM measured flux, it should be emphasised that both SICT and SICM soil covers are capturing, storing, and returning to the atmosphere (through transpiration and evaporation) most of the precipitation that reaches the cover surface. As vegetation becomes more established and the material backfilled into the instrument trench further settles and consolidates, it is expected that significantly less precipitation will percolate into the underlying waste rock.

Table 2 SICT and SICM WFM measured flux

Station	Monitoring Period	Cumulative Estimated Flux (cm)	Average Annual Estimated Flux (cm)	Total Precipitation (cm)	Flux as Percent of Precipitation (%)
SICT	1 April 2009–20 April 2011	8.3	4.1	59.7	14
SICM	1 April 2009–20 April 2011	4.7	2.3	59.7	8

3.3 North Fortitude

The measured water contents at the North Fortitude upper-slope (NFU) station increased in the soil cover and upper waste rock materials in response to infiltration of winter and early spring precipitation (Figure 8). The rapid increase in water content was restricted to the soil cover with a more gradual increase in the waste rock material. The increase in water content through the summer and fall at the deeper waste rock sensor (325 cm bgs) represents the newly installed sensor equilibrating with the surrounding material. A slight increase in water content in spring in response to spring snowmelt and precipitation events is observed at all depths at NFU. Measured water content at NFU produced similar trends to that observed at North Fortitude toe-slope (NFT), with the exception of a sharper wetting response in the waste rock at NFT. Soil water potential data at NFT and NFU also show rapid changes in soil water potential in response to infiltration of winter precipitation (data not shown).

The temperatures in the soil cover and the upper region of underlying waste rock at NFT were generally similar to air temperatures, being slightly warmer in the winter and slightly cooler in the summer (Figure 9). Relatively higher soil than air temperatures were observed at NFU and temperatures increased with depth in the waste rock.

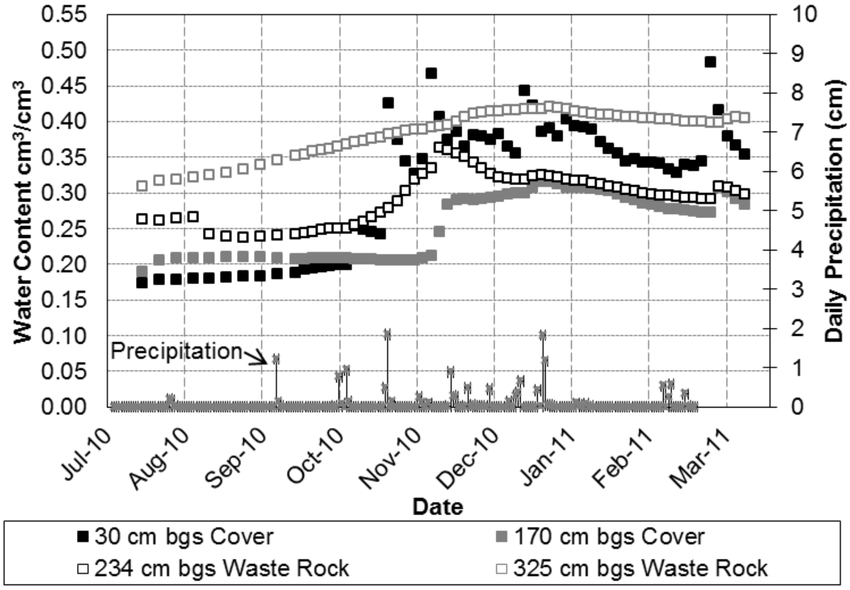

Figure 8 Water content and precipitation at NFU

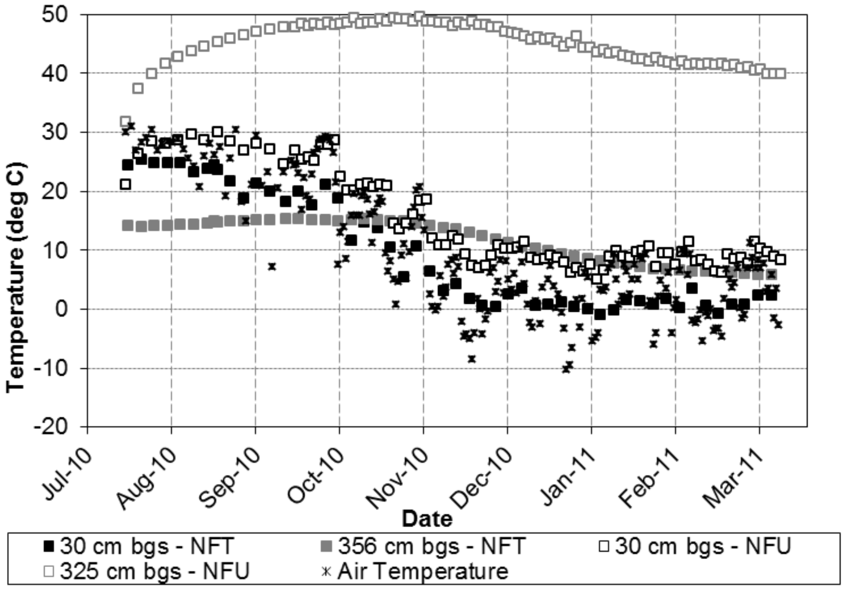

Figure 9 Air and soil temperature at NFT and NFU

Elevated temperatures were observed at the NF geochemical borehole from 6.9 to 23.5 m bgs (Figure 10). This depth interval coincides with waste rock placed at NF in the spring of 2009. Waste rock placed at NF during this time period had an AGP/ANP ratio of less than 1 and a weighted average sulphide content of 3%. In addition, during placement of the waste rock there were four multi-day precipitation events that each totalled greater than 12.5 mm and may have contributed water to the waste rock, resulting in sulphide oxidation. However, water content and soil water potential data from deep waste rock did not indicate trends in wetness and displayed relatively dry and stable conditions (data not shown).

Deep waste rock oxygen contents were less than atmospheric (20.8%), indicting oxidation reactions may be occurring (Figure 11). Oxygen contents remain relatively stable and did not show specific trends with depth. Continued monitoring of oxygen contents, temperature, and water content will allow for estimation of oxidation rates over time. Analysis of vertical air pressure gradients within the waste rock is also taking place to evaluate air flow within the waste rock and its contribution to controlling the geochemical evolution of the waste rock.

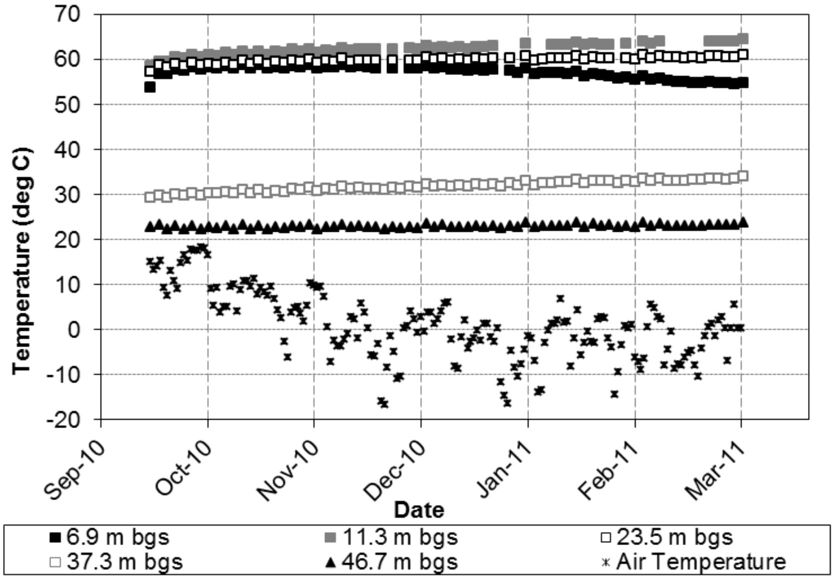

Figure 10 **NFU geochemical borehole air and soil temperature**

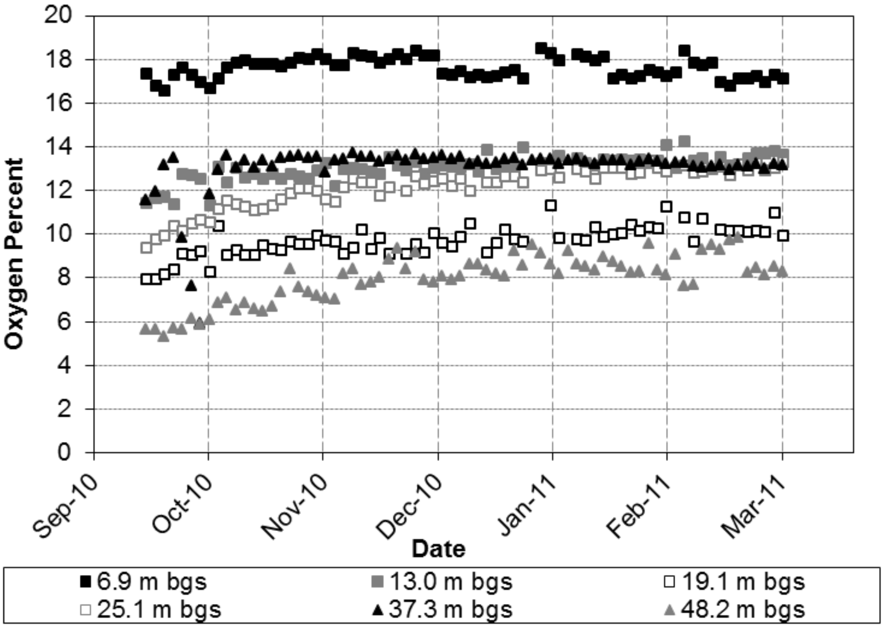

Figure 11 **NFU geochemical borehole oxygen content**

Over this short monitoring period, WFM measured percolation flux at NFT and NFU was less than 1% of precipitation. Monitoring of WFMs over several more wetting and drying cycles will be necessary to determine long-term net percolation flux at these locations.

4 Conclusions

ET cover monitoring at SIC and NF display increases in cover and shallow waste rock water contents in response to infiltration of winter and early spring precipitation (i.e. rainfall and snowmelt) and drying trends (decrease in water content) in late summer and early fall in response to increased ET. Waste rock temperatures at SICM and NFU are higher than air temperatures indicating that sulphide oxidation is occurring. Elevated deep waste rock temperatures and accompanying reduced oxygen contents in the lower lift at the SIC geochemical monitoring well and upper lift in the NF geochemical monitoring well indicate locations of increased pyrite oxidation. At the SIC geochemical monitoring well the addition of water during drilling is likely affecting pyrite oxidation below 36.6 m bgs. Elevated deep waste rock temperatures at the NF geochemical monitoring well coincides with the relatively high sulphide content waste rock placed at NF and a sequence of large precipitation events that occurred while placing this waste rock lift. Continued monitoring of oxygen contents, temperature, and water content will allow for estimation of oxidation rates over time at SIC and NF.

WFM measured percolation flux as a percentage of precipitation for SICT and SICM equal 14 and 8% over a period of 2 years, respectively. Differences between SICT and SICM flux values may be, in part, due to downs-slope water flow converging at the SICT location and coarser cover material at SICT than at SICM. WFM measured percolation flux over the first precipitation season at NFT and NFU was less than 1% of precipitation. Continued monitoring of WFMs over several more wetting and drying cycles will be necessary to determine long-term percolation flux at these locations. Regardless, the soil covers at SIC and NF are capturing, storing, and returning to the atmosphere (through transpiration and evaporation) most of the precipitation that reaches the cover surface. As vegetation becomes more established, it is expected that less precipitation will percolate into the underlying waste rock.

Analysis of vertical air pressure gradients within the waste rock are taking place to evaluate whether air flow within the waste rock is replenishing oxygen and controlling the geochemical evolution of the waste rock. Additionally, measured soil water potential data will be used to develop a one-dimensional vertical flux model for the cover monitoring stations.

Acknowledgements

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