DRA–13. HYDROLOGICAL CHARACTERIZATION OF ROCK PILES

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1. STATEMENT OF THE PROBLEM

What is the hydrological characterization of the Questa rock piles? How can these data be integrated into a hydrological conceptual model? How do the hydrological parameters of the rock pile affect rock-pile weathering and rock pile stability?

2. PREVIOUS WORK

The effect of water on slope stability of rock piles worldwide has been identified in a number of studies. Slope instability can be caused by a number of factors including gravity sorting of waste material during construction of piles, increased overpressure due to increased soil wetness, increased slope angle from soil erosion, loss of material strength due to weathering, and promoted by precipitation or snowmelt events (Tesarik and McKibben, 1999). Donovan and Karfakis (2003) state "Saturation of the slopes and weathering of the slope material are the main reasons the slopes failed, and both are directly due to the presence of water." Slope failures at mine sites typically are associated with a buildup of positive pore pressures within the rock pile, mostly due to heavy rainfall events (Donovan and Karfakis, 2003; Kasmer et al., 2006; Tesarik and McKibben, 1999). McLemore et al. (2008c) summarizes construction and stability of rock piles worldwide.

The weathering processes that occur within the rock piles at mine sites involve the dynamic interaction of the rock-pile material with water, air, sulfur, and microbes. The oxidation of pyrite is one of the predominant weathering reactions in sulfidic mine wastes and is dependent upon the availability of water. These processes can locally lead to a reduction in rock strength by grain size reduction or increased strength by cementation of material (Gutierrez, 2006).

3. TECHNICAL APPROACH

Field and Sampling procedures

Measurements of bulk density were obtained during field investigations. Sampling procedures, descriptions, and analytical analyses typically used for soil profiles were used, since the rock pile material is similar to mine soils (URS Corporation, 2000; Smith and Beckie, 2003; Haering et al., 2004; Stormont and Farfan, 2005). During GHN regrading, the unit boundaries were identified, then samples from each subsurface unit were collected for geochemical, geotechnical (including shear box tests), biological, isotopic, and electron microprobe analyses. Most samples were channel composites collected along approximate 1.5-m-long horizontal slots using a rock hammer to chip material from bench walls and the material was placed into a sample bag. Some samples were composites collected along specific layers that were less than 1.5 m thick and the entire sample was then analyzed. Matric suction, guelph permeameter, and tensiometer measurements were obtained in situ during the mapping and sample collection.

Laboratory Procedures

The laboratory paste tests and gravimetric moisture contents were performed at New Mexico Institute of Mining and Technology (NMIMT) using laboratory procedures (SOPs) established as part of the overall project procedure documentation. Petrographic analyses (mineralogy, lithology, hydrothermal and weathering alteration) were performed using a binocular microscope. These analyses were supplemented by thin section petrography, microprobe, X-ray diffraction analyses, and whole-rock chemical analyses for confirmation. Clay mineralogy, in terms of the major clay mineral groups was determined using standard clay separation techniques and X-ray diffraction analyses of the clay mineral separates on oriented glass slides (Hall, 2004; Moore and Reynolds, 1989). The concentrations of major and trace elements, except for S, SO_4, LOI (loss on ignition), and F, were determined by X-ray fluorescence spectroscopy at the New Mexico State University and Washington State University laboratories. F concentrations were determined by ion probe and LOI concentrations were determined by gravimetric methods at NMIMT. S and SO_4 were determined by ALS Chemex Laboratory. Acid base accounting tests were performed on selected samples (Tachie-Menson, 2006). Hydrogeologic characteristics were established by Shannon (2006). Shear strength, point load, and slake durability were determined by Gutierrez (2006; Gutierrez et al., 2008) and Viterbo (2007; Viterbo et al., 2007).

4. CONCEPTUAL MODELS

A simplified construction model of GHN at the time of construction (time=0) is shown in Figure 1. The Questa rock piles were constructed using standard mining practices of the time. The Questa piles (Fig. 2) were constructed primarily by haul-truck end-dumping in high, single lifts, which involved the dumping of rock over the edge of the hill slopes and resulting pile crests (Fig. 1; URS Corporation, 2000; McLemore et al., 2005, McLemore and the Questa Rock Pile Weathering and Stability Team, 2008). Multiple areas of the open pit were mined at the same time. Records of the quantity, type and location of the overburden material mined from the pit were not maintained. The sequence of rock pile construction was typically from the top down. The upper portion of the rock pile tends to be more soil-like (matrix-supported), whereas the lower portion tends to be rock-like (cobble-supported). The base of the rock pile is coarse rock and cobble supported and is referred to as a boulder rubble zone. The resulting layers are locally at or near the angle of repose and subparallel to the original slope angle. More details are in McLemore et al. (2008a).

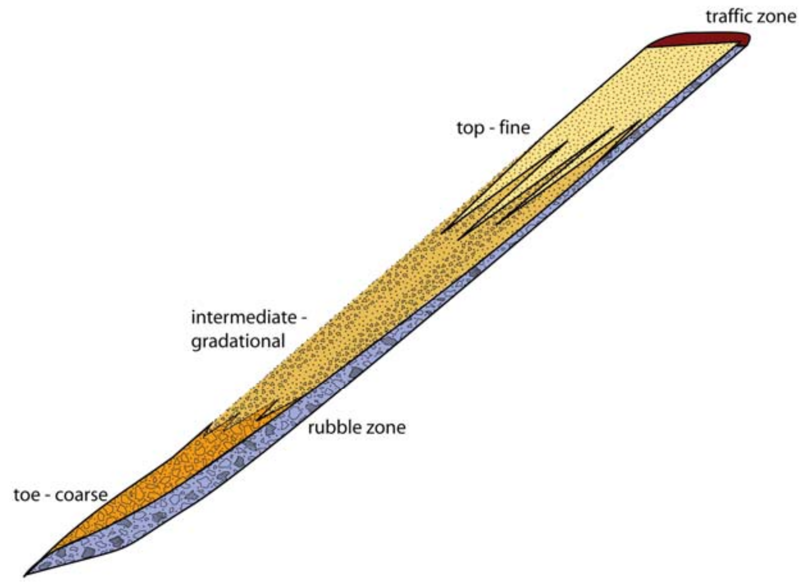

FIGURE 1. Conceptual model of the particle-size distribution of a rock pile constructed by end dumping over the crest of a natural slope of a hill, similar to the construction of GHN and many rock piles in the world (from field studies at GHN and Nichols, 1987, Morin et al., 1991, 1997, Smith and Beckie, 2003).

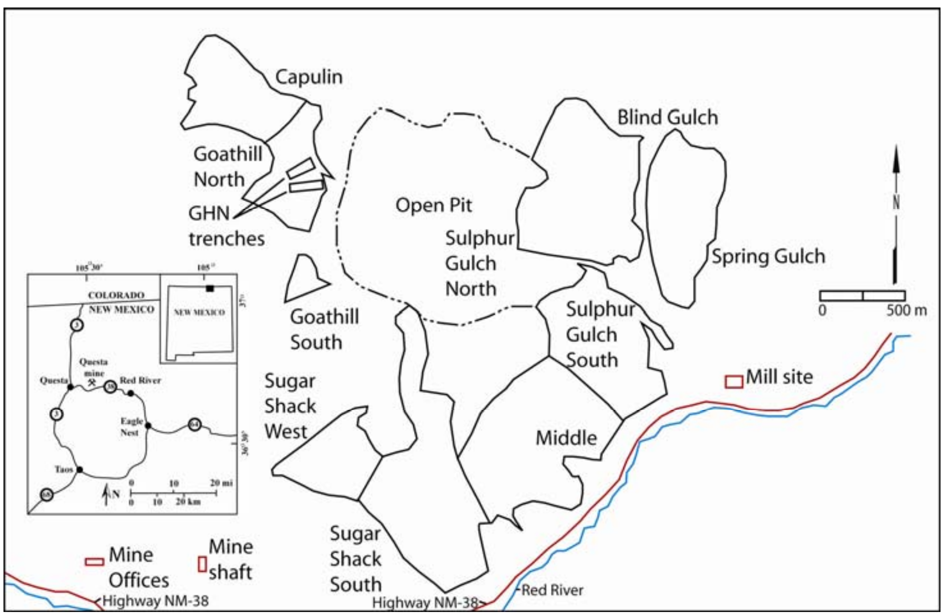

FIGURE 2. Questa rock piles and other mine features, including location of trenches constructed in GHN.

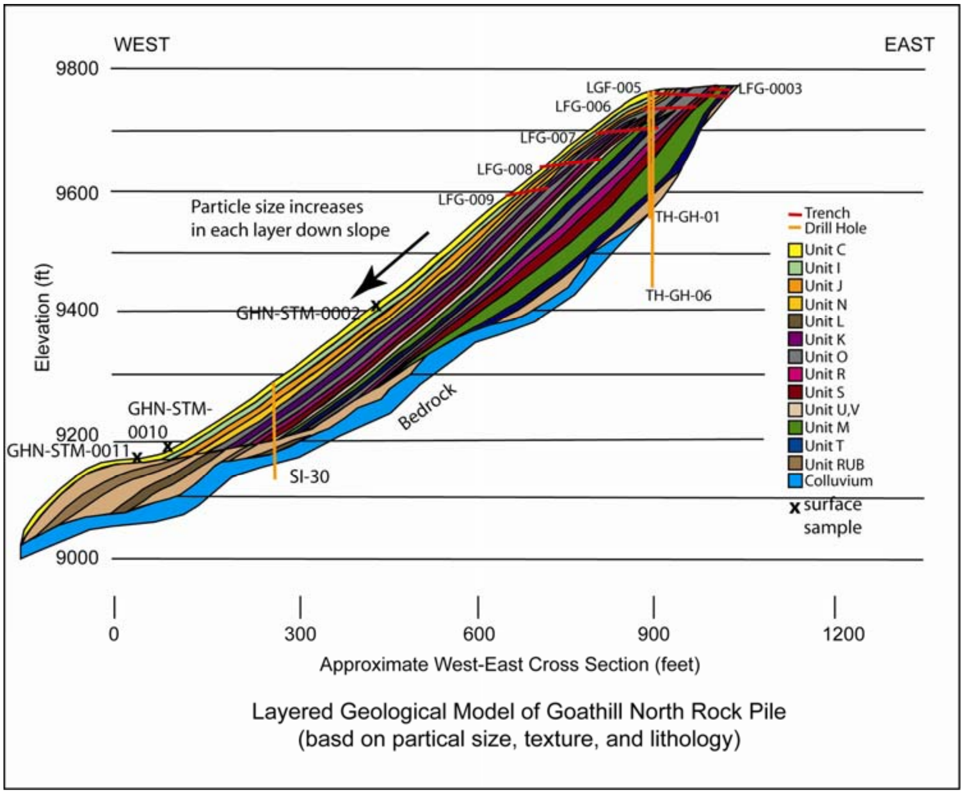

FIGURE 3. Conceptual geological model of GHN rock pile, as interpreted from surface mapping, detailed geologic cross section (Appendix 2), trenches, drill holes, construction method and observations during reclamation of GHN (McLemore and the Questa Rock Pile Weathering and Stability Team, 2008).

Water in the rock-pile system originated as infiltration of local meteoric water (DRA-28, 29; Campbell and Hendrickx, 2008). The precipitation that feeds the system is very dilute, as is all natural precipitation (Berner and Berner, 1996). Water chemistry in the rock pile evolves due to air-water-rock chemical interactions in pore spaces along the flow paths. In Figure 4, rock clasts and minerals of ranging composition are shown schematically in colors. Pore space, shown in light blue, is under negative pressure, but there can be film flow across solid surfaces and intra-rock pores (and some very small inter-rock pores) may be saturated or nearly so. A conceptualization of the physical system at small scale is shown in Figure 5. The major phase regions associated with this model are described further in Table 1, which also presents representative proportions of the total volume, based on controlled experimental results at bench scale (L.M. Cathles, personal communication, 2006; 1994; Calthes and Apps, 1975). As a result of rock pile settlement, it is expected that the bulk porosity of typical rock piles will decrease by up to 10%, usually over a few years to perhaps a decade (Oldecop and Alonso, 2007). Note that in rock piles, or portions of rock piles, with a high percentages of fines, the proportion of pore space filled by liquid water (V_l) will increase and, conversely, that filled with air (V_g) will decrease over time as the pile "wets up", because the fines can retain higher moisture contents due to capillary forces than can coarse particles with large voids (DRA-28, 29).

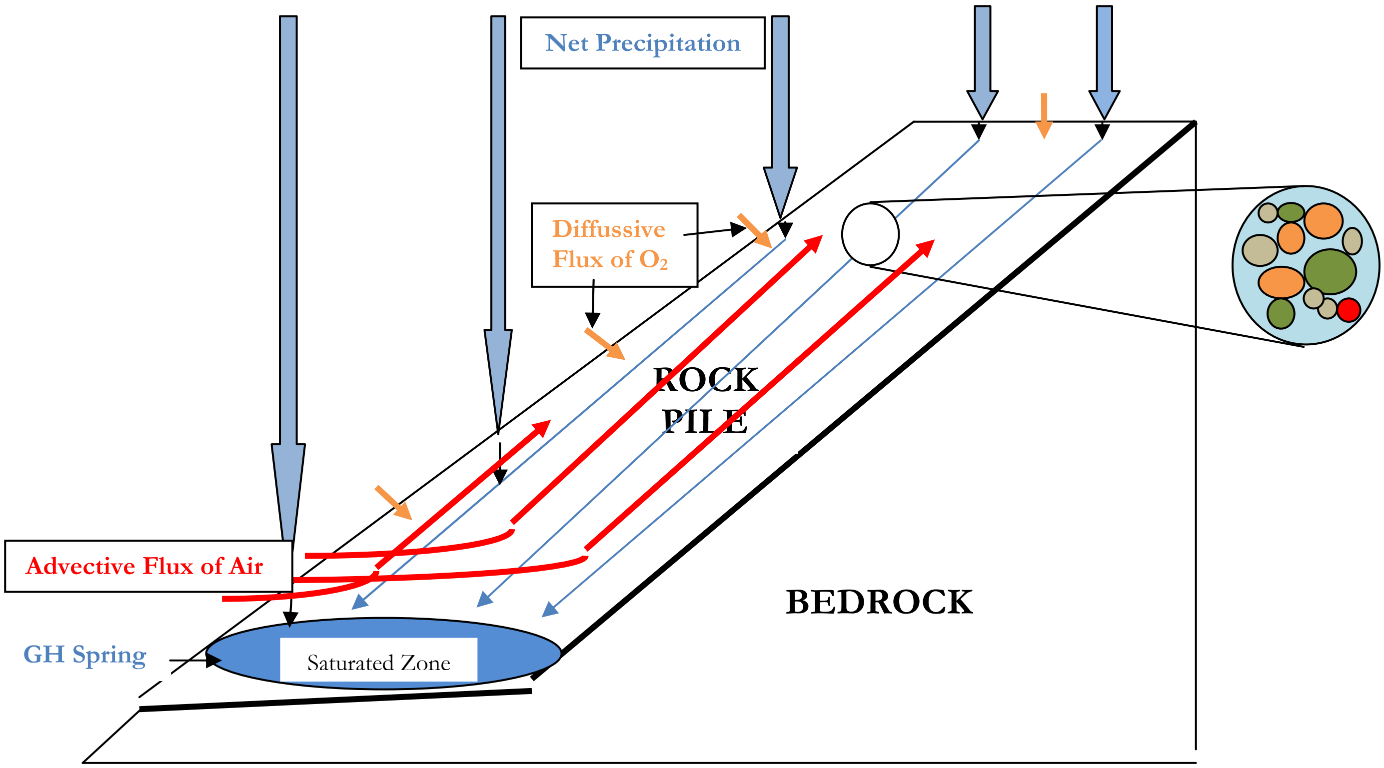

FIGURE 4. Conceptual model of fluid flow, Goathill North rock pile (GHN), with Goathill Spring (GH Spring) from DRA-28, 29. Net Precipitation = [Ppt-(Runoff +Evap)] = Infiltration. Counter-current flow of water downward (gravity) and air upward (buoyancy). Additional O_2 flux by diffusion across surface. Note that the advective flow of air into the pile also includes water vapor.

As water is added to the rock pile (by percolation of infiltrating precipitation, and locally along the sole of the rock pile by flow of bedrock water in fractures that debouches into mined rock of the pile), the boundary-layer flow over rock particles increases, and at some point "bottlenecks" in inter-rock voids form as boundary layers overlap. At this stage, flooding of the bottlenecked pore occurs, with water filling the bottlenecked void and flowing then to the next most permeable zone above the bottleneck, again as film flow. The unsaturated pores below the bottleneck remain drained, and flow goes to fewer and fewer, but more and more, permeable channels. Over time, fine layers (or matrix-supported layers that also include clasts) will become closer to saturation (negative pressures decrease), and the volumetric (and mass) flux of water downward under gravity through the fines will increase (DRA-29). Although probably never in a strictly true, physical steady-state, variations in flow associated with storm events and even seasonality typically dampen with depth (Freeze and Cherry, 1979), and deep percolation of water, averaged over areas of tens to hundreds of square meters, steadies (DRA-28, 29).

Clast-supported boulder layers, in contrast to matrix-supported, fine-grained layers which retain moisture, have inter-rock voids too large to allow significant saturation (DRA-28, 29). These zones, which can be continuous over some tens to perhaps locally 100 meters along depositional strike of the sediments (Fig. 3; DRA-6; McLemore et al., 2008a), are connected tortuously in the pile, and the coarse, clast-supported zones are the principal loci of convective air flow. The driving force for convective flow is buoyancy, derived primarily by heating (due to the exothermic pyrite-oxidation process; DRA-7; McLemore et al., 2008a) as air reacts with sulfides in the rock pile. Flow of liquid water in the coarse layers is limited to film-flow across boulder surfaces. Although the rock pile is unsaturated, water percolates downward through the pile under gravity and matric suction gradients, primarily in fine-grained materials as discussed above, while air moves predominantly upward, and through the most permeable channels. The counter-current flow of water and air is shown schematically in Figure 4. The counter-current flow system develops because the construction of truck-dumped rock piles produces a dual distribution of permeabilities, with lower permeabilities in the fine-grained matrix material and much higher, probably at least two orders of magnitude higher, permeabilities in the clast-supported coarse layers (DRA-28, 29; McLemore et al., 2008a).

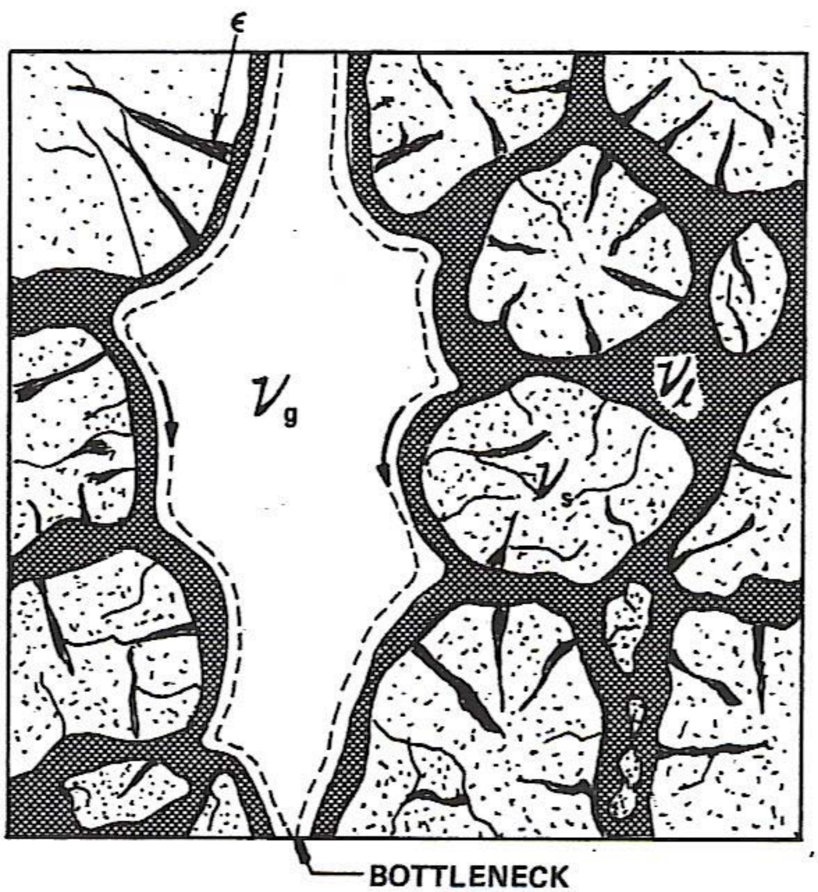

FIGURE 5. Schematic static section through rock pile (DRA-28, 29). Rock solid (V_s); Primary rock porosity (ε); Gas (air)-filled void (V_g); Water-filled void (V_l). Figure based on

unpublished report of work conducted in 1977 (personal communication from L.M. Cathles, 2006).

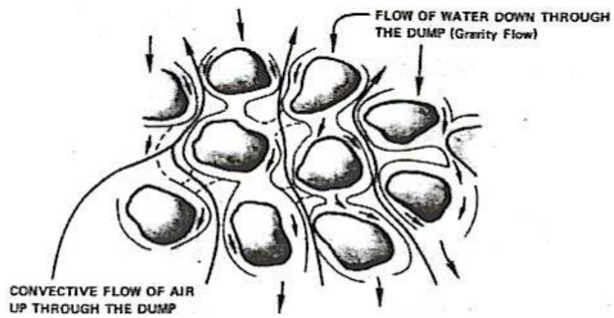

FIGURE 6. Schematic dynamic section through rock pile (DRA-28; From Cathles and Apps, 1975). Countercurrent interlocking flow of air and water through a leach dump. The flow of water is usually intermittent.

TABLE 1. Phase regions – Terminology (After unpublished report of work conducted in 1977, personal communication from L.M. Cathles, 2006).

Phase	Symbol (Fig. 2)	Dynamics	Test-Column (Volume Percent)
Solid rocks, including closed (but not open) pores within rock	V_s	Stagnant (dead space)	59%
Open porosity within rock	E	Stagnant (dead space)	2%
Water-filled void space between rocks	V_l	Mobile to aqueous solution	19%
Gas (air)-filled space between rocks	V_g	Mobile air flow or trapped air pockets	19%

At depth within the GHN rock pile, the unsaturated flow accumulates in a locally perched, saturated zone that integrates the water chemistry as well as the physical flow (DRA-28, 29). The accumulation of infiltration is concentrated at the interface of the rock pile with underlying, fine-grained and poorly transmissive colluvium, the permeability contrast allowing a perched zone of hydraulic saturation to form and persist locally (SRK, 2007).

5. STATUS OF COMPONENT INVESTIGATION

Field and laboratory data characterizing GHN

Particle size

Particle size analyses, including hydrometer analyses, were performed on trench samples from GHN (Fig. 7). Summary statistics are in McLemore et al. (2008a). Most of the samples were classified as poorly-graded or well-graded sandy gravel with small percentage of fines. GHN rock pile consisted of alternating layers of thin cobble supported coarse-grained and thicker layers of matrix-supported finer-grained zones. The layers coarsen down slope in the final trench, LFG-009, where most of the units consisted of coarse sand, gravel, cobbles, and boulders and less fine sand, silt, and clay than the same stratigraphic units up slope in trench LFG-008.

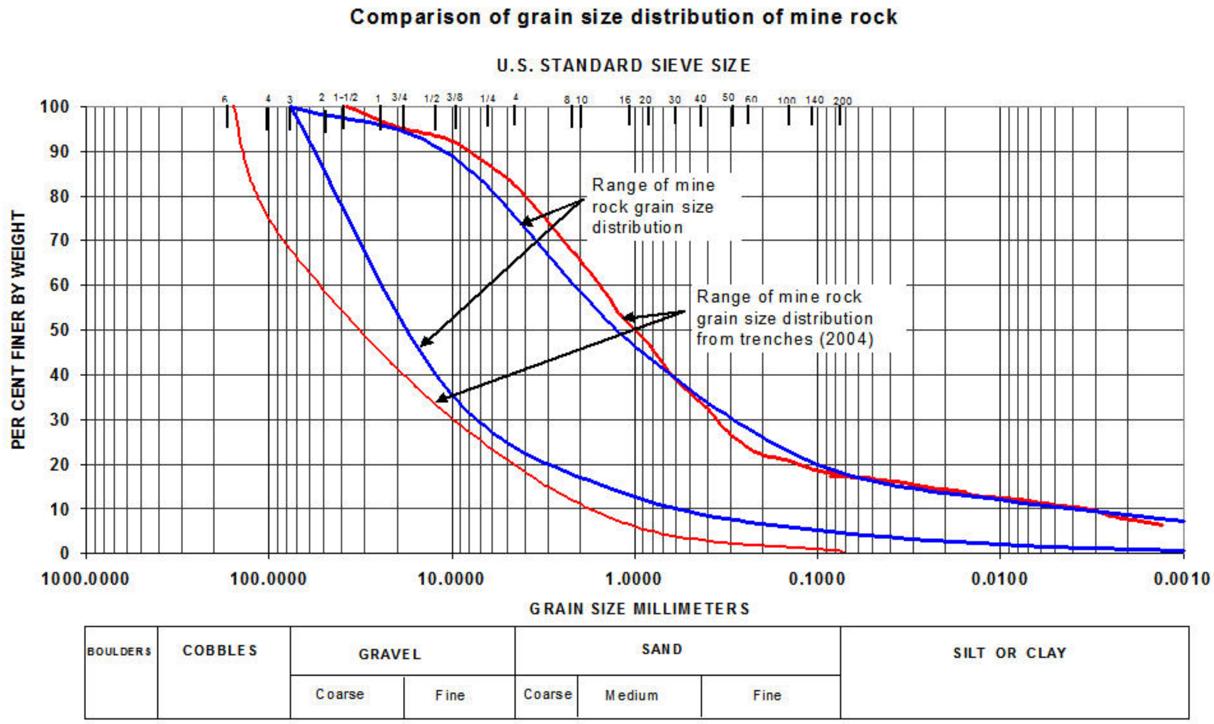

FIGURE 7. Particle size analyses of selected samples from GHN compared to legacy data from company reports. The blue lines are from data in URS Corporation (2003) and the red lines are from data obtained in this study from GHN.

Porosity and permeability

The porosity from drill hole samples from company reports varies from 0.2 to 0.47% (project database). The void ratio varies from 0.52 to 0.89%. The permeability of drill hole samples from company reports varies from 0.0136 to 2.09 cm/sec using rigid wall permeability test results. Tables 2-4 summarize the data on GHN.

TABLE 2. Volume-mass properties of the soils/tailings collected from Golder Associates (2005a, b).

ID	Soil region	Degree of saturation, S (%)	Specific gravity, G	Gravimetric water content, w (%)	Porosity, n (%)
1	TP-4	100	2.65	10.64	22.0
2	TP-5	100	2.65	25.1	39.9
3	TP-6	100	2.65	19.9	34.5
	Average			18.54	32.12

TABLE 3. Volume-mass properties of the soils/tailings collected from Norwest Corporation (2004).

ID	Soil region	Degree of saturation, *S* (%)	Specific gravity, *G*	Gravimetric water content, *w* (%)	Porosity, *n* (%)
1	SSU-3 (TP-5)	100	2.65	8.7	18.7
2	TP-4-2B	100	2.65	19.6	34.2
3	SG-2	100	2.65	19.6	34.2
	Average			14.5	29.03

TABLE 4. Volume-mass properties of the soils/tailings measured using Tempe Cell measurements (M. Fredlund, written communication, April 13, 2006).

ID	Soil region	Degree of saturation, *S* (%)	Specific gravity, *G*	Gravimetric water content, *w* (%)	Porosity, *n* (%)
1	GHN KMD 0016	100	2.65	35.2	48.3
2	KMD 018	100	2.65	21.1	35.9
3	KMD 053	100	2.65	23.7	38.6
4	GHN KMD 0065	100	2.65	29.2	43.6
5	LFG SCS 005	100	2.65	31.3	45.3
6	GHN LFG 001	100	2.65	35.9	48.8
7	LFG 003	100	2.65	24.6	39.5
8	GHN LFG 004	100	2.65	35.1	48.2
9	GHN LFG 006	100	2.65	36.5	49.2
10	PIT LFG 001	100	2.65	32.3	46.1
11	PIT LFG 003	100	2.65	25.4	40.2
12	PIT LFG 005	100	2.65	32.7	46.4
13	PIT LFG 007	100	2.65	23.1	38.0
14	PIT LFG 009	100	2.65	20.2	34.9
15	PIT LFG 0013	100	2.65	36.0	48.8
	Average			29.5	43.5

Density/specific gravity

McLemore et al. (2008a, table 35) summarizes the descriptive statistics for the GHN and other Questa materials; histograms and summary of statistical analyses are in McLemore et al., 2008a; appendix 10). There is not a statistically significant difference between the dry densities of various geologic units within GHN (McLemore et al., 2008a, appendix 11). Therefore, the average density for GHN rock piles is 1.8 g/cc. The density of the GHN samples is statistically similar to other Questa rock piles, debris flows and alteration scars.

Specific gravity measurements were performed on samples from the GHN rock pile and elsewhere in the Questa area (McLemore et al, 2008a, table 35). The material used for testing passed a no. 4 sieve and sample sizes were generally between 100 and 110 grams. Specific gravity measured between 2.6 and 3.0 g/cm^3 for all samples with approximately two thirds falling between 2.6 and 2.7 g/cm^3.

Gravimetric moisture content

Results of gravimetric moisture contents are presented in McLemore et al. (2008a, table 36). Gravimetric moisture contents ranged from 2 to 24% near the surface of the rock piles, but values measured in trenches within the GHN rock pile were typically between 6 and 20%. The top of GHN rock pile appears to have higher moisture contents than the base of the rock pile. There is no stastical difference between the gravimetric moisture content of the outer units (units C, I, J) from the interior units (units K, N, O, M, R, S, T, U, V, and W) and the basal rubble zone (unit RUB; McLemore et al., 2008a, appendix 11).

Infiltration and hydraulic conductivity

Tensiometers were installed on the top of GHN in June 2004 in hand-dug holes in two nests, one in an uncompacted region and one in a compacted region to provide information about the matric potential response of the rock pile to precipitation events (SOP 43). The infiltration rates that were measured on several different surfaces using the tension infiltrometer ranged between 0.07 and 3.0 cm/min (McLemore et al., 2008a). The infiltration rates were measured at different matric suctions, ranging from near saturation at approximately –1.5 cm of suction (saturation is at 0 cm) to –30 cm of suction. The higher matric suctions resulted in the lowest infiltration rates whereas the lower matric suctions resulted in the highest infiltration rates. Therefore, when the rock pile is drier (higher matric suctions), it is more difficult to infiltrate water into the system than when the pile is wetter (lower matric suctions).

The guelph permemeter measures saturated hydraulic conductivity, whereas the tension infiltrometer can be used to measure the saturated and unsaturated hydraulic conductivity. Twenty-one tension infiltrometer measurements were made in 2004 at GHN (McLemore et al., 2008a, fig. 113, appendix 7). The data collected were used to estimate the saturated hydraulic conductivity (Ksat = K(h), where h = 0 cm). The measurements were made on the top and middle bench of the GHN rock pile prior to the regrading phase. There was significant variability in the measurements made on the different parts of the pile. The guelph permeameter was used to make 47 measurements of the saturated hydraulic conductivity. The measurements were made in 2003-2005. Numerous tension infiltrometer measurements were made at the same and different locations in the trenches as prior guelph permeameter measurements (Project database; McLemore et al., 2008a).

Evaporation

A literature review was performed to determine the annual evaporation or potential evapotranspiration in the Questa mine vicinity. Numerous studies that were previously completed on the mine facilities estimated the annual evaporation rates using pan evaporation techniques, lysimeter data, and meteorological data. Wels et al. (2001)

estimated annual pan evaporation for the region near the tailings facility as approximately 65-70 inches. After installing a meteorological station, the cumulative potential evapotranspiration was estimated to be 14.04 inches from Aug. 9, 2000 to Jan. 6, 2001. A summary of the four lysimeter test plots for the first year of monitoring (July 2000–July 2001) determined that cumulative potential evaporation reported in inches for each station is as follows: TP-4 = 47.8, TP-5 = 36.7, TP-6/TP-7 = 45.0 (Robertson GeoConsultants, 2003). Evapotranspiration (in inches) was estimated as: TP-4 = 6.54, TP-5 = 3.43, TP-6 = 4.44, and TP-7 = 4.90 (Robertson GeoConsultants, 2003). Golder Associates, Inc. (2005) estimated the annual evaporation for the rock piles from 1965-2003 as 12.6 inches (Table 3).

Stable isotopes and modeling indicate that evaporation at and near the surface is an important process in moving water out of the rock pile (DRA-12). Stable isotopes (δD and $\delta^{18}O$) in water samples help constrain certain aspects of the hydrology of the rock piles. The investigation focuses on the seasonality of recharge, the degree of evaporation, and the vapor transport within the pile. Winter precipitation as snow tends to be isotopically light compared to summer precipitation. Evaporation was determined to be important; during evaporation, the light isotopes (H and ^{16}O) are preferentially partitioned into the vapor phase while the heavy isotopes (D and ^{18}O) are retained in the liquid phase.

Matric suction

Handheld tensiometers were used to collect 144 matric potential values from GHN in 2004 and 2005 and other areas in the mine site from 2004 to 2007 (McLemore et al., 2008a, appendix 7). The data were used to provide an understanding of the hydraulic properties of the distinguishable layers in the trenches. The matric potential values in the trenches ranged between –20 kPa and –1 kPa and the median matric potential was –5 kPa. The values vary significantly and do not provide any information about how the matric potential will vary with time in a particular place; they simply provide useful information for the present state of the pile at the time of the measurement. There is no correlation between matric suction and gravimetric moisture content (McLemore et al., 2008a, fig. 115).

Water chemistry

The chemical analyses of water samples collected from seeps at the toe of GHN before reclamation are characterized by high acid (low pH), high sulfate, high TDS (total dissolved solids), and high metal concentrations (McLemore et al., 2008a;DRA-28). Sulfate is the predominant anion and Al, Mg, Fe, Mn, and F are the predominant cations and anions. These are products of weathering within the rock pile. The chemical analyses of the GHN waters reflect the dissolution of calcite and pyrite. The high Mn is related to Mn-bearing carbonate (calcite, dolomite, rhodochrosite), chlorite, and epidote. The high fluorine is related to dissolution of fluorite and clay minerals illite and smectite, which contain anomalous fluorine concentrations. The high Al is related to leaching of Al-bearing silicate minerals (feldspars, clay minerals, epidote).

6. RELIABILITY ANALYSIS

Only the upper third of the GHN rock pile was trenched, mapped, and sampled, although three drill holes also were drilled into the lower portion of the rock pile. The data was extrapolated for the entire rock pile. Samples from the surface of the toe of GHN were used to define the toe region. Only two dimensions were modeled.

The GHN rock-pile materials are a mixture of different lithologies and hydrothermal alteration mineral assemblages before being emplaced in the rock piles, therefore changes of mineralogy and chemistry between the outer, oxidized zone and the interior, unoxidized zones of the rock pile are a result of differences due to pre-mining composition as well as chemical weathering. These differences can be difficult to distinguish.

7. CONCLUSIONS OF THE COMPONENT

- The mean bulk density of the rock pile material ranged between 1.60 g/cm^3 and 2.21 g/cm^3 for mapped soil regions within the Goathill North rock pile.
- The mean and median saturated hydraulic conductivity (*Ks*) of the rock pile material estimated from tension infiltrometer measurements were 8.32E-03 cm/s and 9.07E-04 cm/s, respectively. Note that these values apply to the finer-0grained, soil-like matrix0supprted zones. They do not apply to the coarse-grained, clast-supported zones, in which the field instrumentation cannot be used
- Guelph permeameter measurements estimates for the mean and median saturated hydraulic conductivity were 2.32E-02 cm/s and 7.31E-03 cm/s, respectively, significantly higher than the tension infiltrometer estimates.
- Field measurements of matric suction using hand-held tensiometers indicated that the rock pile was relatively moist with a mean suction value of –61 cm between early September 2004 and early October 2004. Records from nested tensiometers also indicated a wet regime between June 2004 and August 2004, ranging between –80 cm and saturation.
- Modeling by Shannon (2006) showed that the moisture distribution within the generic rock pile containing soils without rocks was relatively homogeneous.
- Modeling by Shannon (2006) also showed that storage of water in soil, which is directly related to the soil porosity and other soil properties, is the most significant parameter explaining the moisture distribution within the pile. In addition, the investigation shows that the rocky soils respond most quickly to rainfall events, and lead to wetter-moisture conditions due to the low porosity and therefore low water storage capacity of these soils.

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