DRA–6. WEATHERING OF GOATHILL NORTH (GHN) ROCK PILE

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1. STATEMENT OF THE PROBLEM

Are there systematic changes due to weathering from the outer edges to the interior and base of the Goathill North (GHN) rock pile? If so, how can these be integrated into a conceptual model of rock-pile weathering that could be used to assess the impacts of weathering on shear strength and pore pressure? The purpose of characterizing GHN was to describe the structure, stratigraphy, physical, chemical, mineralogical, hydrological, and geotechnical characteristics and extent of weathering of the rock pile. These characteristics will be used to model the GHN rock pile and to model future weathering and slope stability of the Questa rock piles.

2. PREVIOUS WORK

Weathering of rock piles at the surface is common world-wide. At Aitik, Sweden, pockets of more oxidized material are found within the rock pile, especially near the edges (Linklater et al., 2005). Mineralogical studies of the Laver tailings in Sweden showed (Ljungber and Ohlander, 2000) four zones of weathering: 1) low sulfides in the uppermost, oxidized portion, 2) sulfide minerals with surface coating of Fe-oxyhydroxides, 3) edges of biotite were slightly oxidized, and 4) no other silicate minerals were oxidized. Mineralogic and chemical studies of the high-sulfide mine-wastes at the Berikul mine in the Kemerovo region, Russia, delineated five zones of weathering (Sidenko et al., 2005): 1) upper-most jarosite zone, 2) intermediate zone, 3) melanterite zone, 4) cemented hardpan zone, and 5) slightly altered basal waste zone. McLemore et al. (2008c) summarizes the construction and weathering of rock piles worldwide.

3. TECHNICAL APPROACH

Mapping procedures

Remote sensing techniques were used to map the sulfate and clay mineralogy on the surface. Ground penetrating radar surveys (van Dam et al., 2005) and thermal camera imaging surveys (Shannon et al., 2005) were used to select the location of trenches within GHN rock pile during reclamation. Standard geologic mapping techniques were used (Lahee, 1961; McLemore et al., 2005). Each unit on the surface and in the subsurface of GHN was examined, mapped and described. The units were differentiated mostly on the basis of color, grain size, lithologic composition, texture, stratigraphic position, dip, thickness, and other soil properties (Appendix 1; McLemore et al., 2005, 2006a, b, 2008a). Longitudinal sections were made of each bench in the GHN rock pile and geologic maps were made for each trench (McLemore et al., 2008a). The project geologic mapping, work plans, and standard operating procedures (SOPs) describe the mapping and field procedures that were used in this study. Specific location and construction data for each trench is in the project database (McLemore et al., 2004) and GIS_trenches ARCMAP project.

Sampling procedures

Sampling procedures, descriptions, and analytical analyses typically used for soil profiles were employed, since the rock-pile material is similar to mine soils (URS Corporation, 2003; 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 5-ft-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 5 ft thick and the entire sample was then analyzed. Sample locations are in Figure 1, Appendix 2 (this report) and McLemore et al. (2008a, appendices 4-6). Appendix 3 (this report) lists the samples for each trench or drill hole shown in Figure 1.

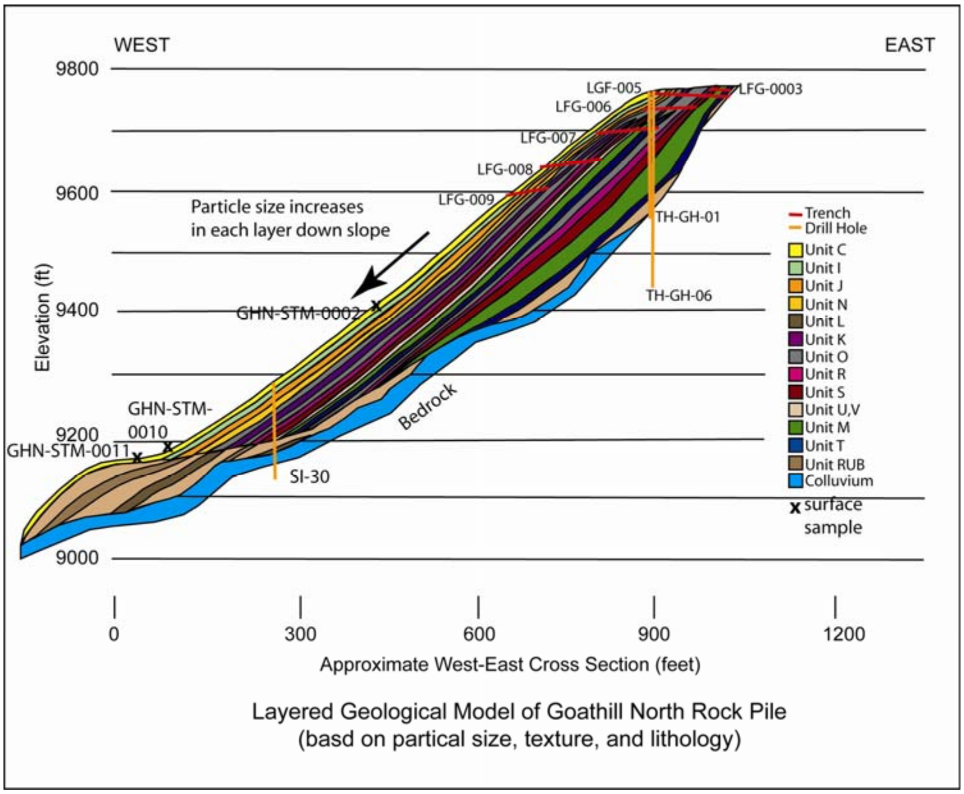

FIGURE 1. Conceptual geological model of GHN rock pile showing sample locations, as interpreted from surface mapping, detailed geologic cross section (Appendix 2), trenches, drill holes, construction method and observations during reclamation of GHN (McLemore and the Questa Rock Pile Weathering and Stability Team, 2008).

Laboratory Procedures

The laboratory paste tests (paste pH, paste conductivity, etc.) 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 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). This method does not liberate or measure the amount of clay minerals within the rock fragments. 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 fusion and single-element electrode and LOI concentrations were determined by gravimetric methods at NMIMT. S and SO_4 were determined by ALS Chemex Laboratory. The modified ModAn technique (McLemore et al., 2009; DRA-5) provides a quantitative bulk mineralogy that is consistent with the petrographic observations, electron microprobe analysis, clay mineral analysis, and the whole-rock chemistry of the sample. Unlike most normative mineral analyses, all of the minerals calculated for the bulk mineralogy are in the actual sample analysis using ModAn. ModAn is a normative calculation that estimates modes "…by applying Gaussian elimination and multiple linear regression techniques to simultaneous mass balance equations" (Paktunc, 1998, 2001) and allows location-specific mineral compositions to be used. Representative mineral compositions for minerals in the Questa samples were determined from electron microprobe analysis and used in ModAn for this study (McLemore et al., 2009). 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). A flow chart showing the analyses of selected samples is in Figure 2 and described in more detail in DRA-0.

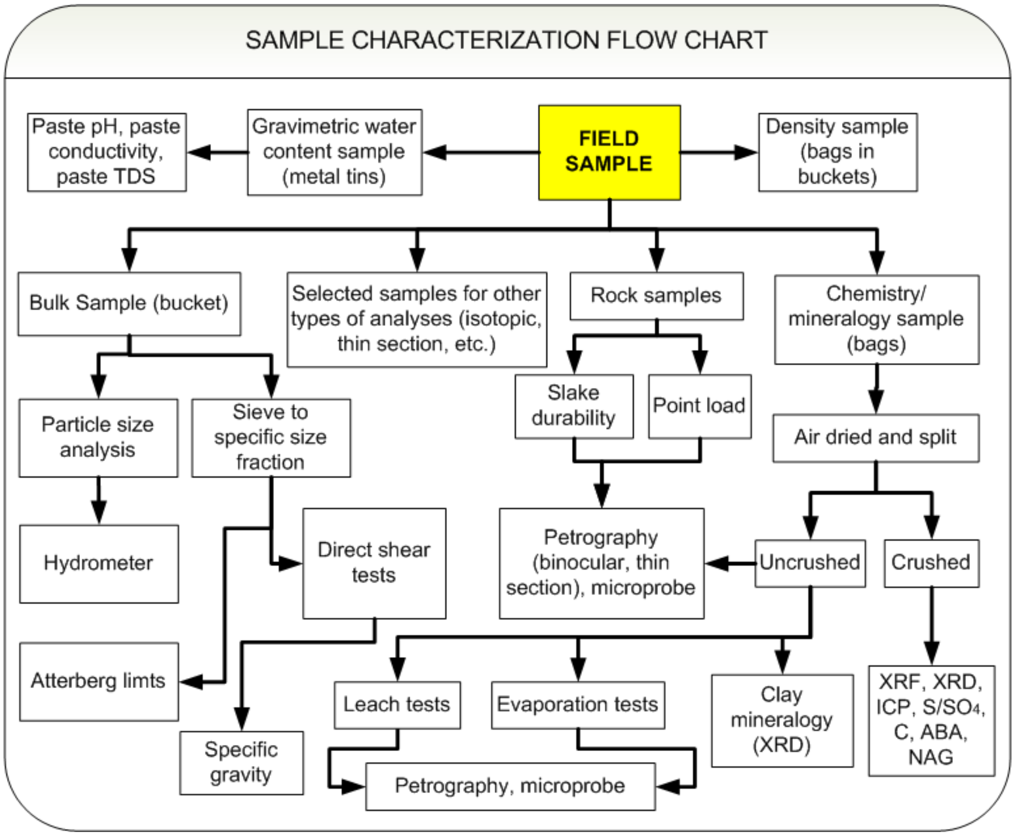

FIGURE 2. Flow chart showing analyses of selected samples. Not all analyses are performed on every sample. Bucket, metal tin, and bags refers to size of sample collected. XRF–X-ray fluorescence analyses, XRD–X-ray diffraction analysis, ICP–Induced-coupled plasma spectrographic analysis, NAG–net acid producing tests, ABA–acid base accounting tests.

4. CONCEPTUAL MODELS

A simplified construction model of GHN at the time of construction (time=0) is shown in Figure 3. The Questa rock piles were constructed using standard mining practices. The Questa piles (Fig. 4) 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. 3; URS Corporation, 2003; 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, lithology, and rock-pile location of individual overburden material were not maintained during construction of the rock piles, which was normal practice in the industry at the time. An estimate of the construction history of the rock piles was determined by examination of aerial photographs, which is summarized in a report by URS Corporation (2003). The sequence of rock pile construction was typically from the top down as a result to the practice of end dumping off the edge of valley slopes. 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).

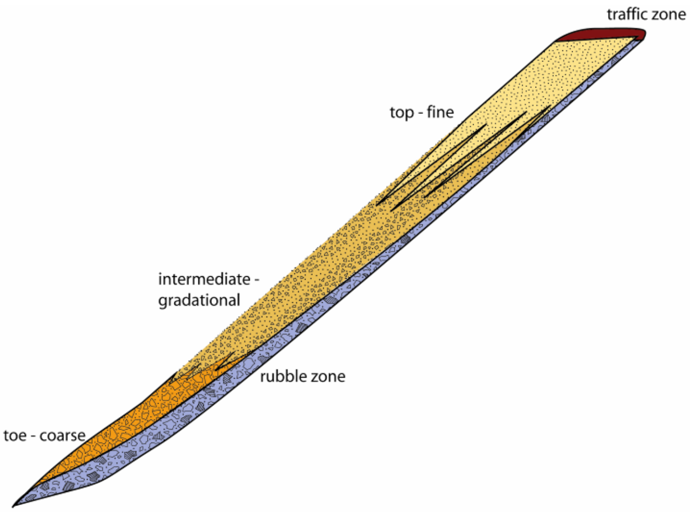

FIGURE 3. Conceptual model of the particle-size distribution of a rock pile constructed by end dumping over the crest of a natural slope of a hill, similar to the construction of GHN and many rock piles in the world (from field studies at GHN and Nichols, 1987, Morin et al., 1991, 1997, Smith and Beckie, 2003).

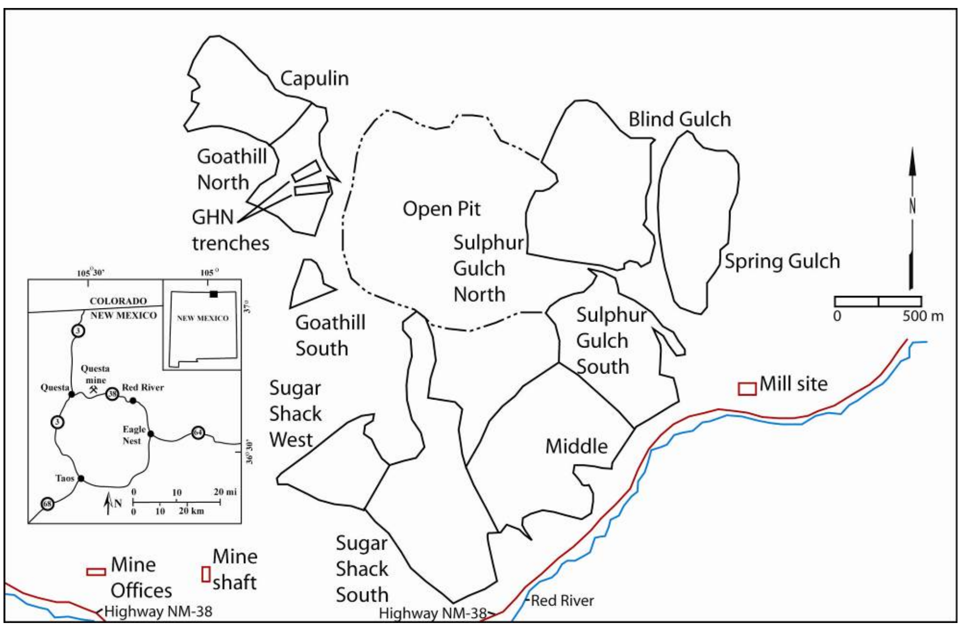

FIGURE 4. Questa rock piles and other mine features, including location of trenches constructed in GHN.

Figures 1 and 4 show the location of trenches constructed in GHN during reclamation. The GHN rock pile is stratified consisting of heterogeneous and locally alternating layers and lenses of coarse- and fine-grained rock-pile material that increase in grain-size down slope (Fig. 1). Geologic units can be defined and correlated down slope through the rock pile. The geologic units typically consist of numerous elongate to lobate, wedge-shaped lenses and layers of a few centimeters to a meter in thickness and were differentiated mostly based on similar color, grain-size, lithologic composition, texture, stratigraphic position, and other soil properties (Appendix 1). Individual layers pinched and swelled or graded vertically down slope or laterally across the width into other lenses. Very few individual layers are continuous through the entire length of the rock pile, but many of the geologic units do appear to be continuous until cut off by the coarse rubble zone forming the toe of the rock pile. Rock fragment lithology is generally consistent within mapped geologic units and correlates well with mineralogy and chemistry. The units in GHN are generally youngest to oldest on the basis of stratigraphic position because the relative time of deposition of the units in GHN increases from west to east. Unit boundaries ranged from horizontal to vertical, but most dipped between 20° and 40° westward to northwestward. A specific geologic unit probably represents a combination of 1) similar lithologic composition of overburden material mined from the upper portion of the open pit and dumped by individual truck loads, 2) aqueous movement in finer-grained material down slope and vertically through the rock pile material by rain-fall events in between individual truck loads, 3) differences in hydrothermal alteration and 4) subsequent weathering of the rock-pile material. Note that all rock piles are different in terms of their construction, composition of overburden materials (including hydrothermal alteration), and weathering, therefore this model only represents the stable portion of GHN rock pile and similar constructed rock piles.

Four different zones of weathering can be distinguished at GHN (Fig. 5):

- outer oxidized zone (includes the surface and geologic units C, I)
- intermediate zone (includes unit J, N)
- inner, less oxidized, weathered zone (includes units K-W)
- basal oxidized zone (includes geologic units R and rubble zone).

Apparently chemical reactions within the main portion of the GHN rock pile are controlled by the availability of oxygen and water. In all benches and drill holes sampled, the interior, less oxidized units (east, units K-W, excluding unit N) of the piles are uniformly dark to light brown or gray with visible pyrite that are interbedded with occasional yellow to gray zones of oxidation associated with little or no pyrite. The inner, less oxidized zone typically contains abundant calcite, chlorite, and clay minerals and accordingly, has high paste pH values and lower acid generating potential than the outer units. The outer surface-atmosphere interface represents a zone with the most active geochemical processes noted in the rock piles. The outer, oxidized units consist of highly leached and oxidized rock comprised mainly of quartz and secondary iron sulfates, with smectite and mixed layer illite-smectite and some pyrite. This zone is characterized by low paste pH, low acid neutralizing potential, and high acid generating potential. Extensive interchange of water and oxygen occurs in this zone, which enhances pyrite oxidation. Inside the leached zone (J) is a zone of clay accumulation. The clays are predominantly illite and smectite with increasing chlorite toward the center of the pile. This unit is typically green to orange with moderate to low paste pH. Inward from the zone of clay accumulation is a zone of sulfate mineral accumulation. Jarosite and gypsum become more abundant and the zone is typically orange. In between the outer, oxidized and interior, unoxidized zone is an intermediate zone (Unit N) of light to dark brown material that is well cemented by clay. It contains local zones of bright orange to yellow oxidized sandy clay. Clays are dominated by illite, smectite, and chlorite. Proximal to the interface are zones of dark brown to black accumulation of iron or manganese oxide material that coat grains and clasts. This accumulation of iron and manganese oxides could possibly represent a zone of reduction.

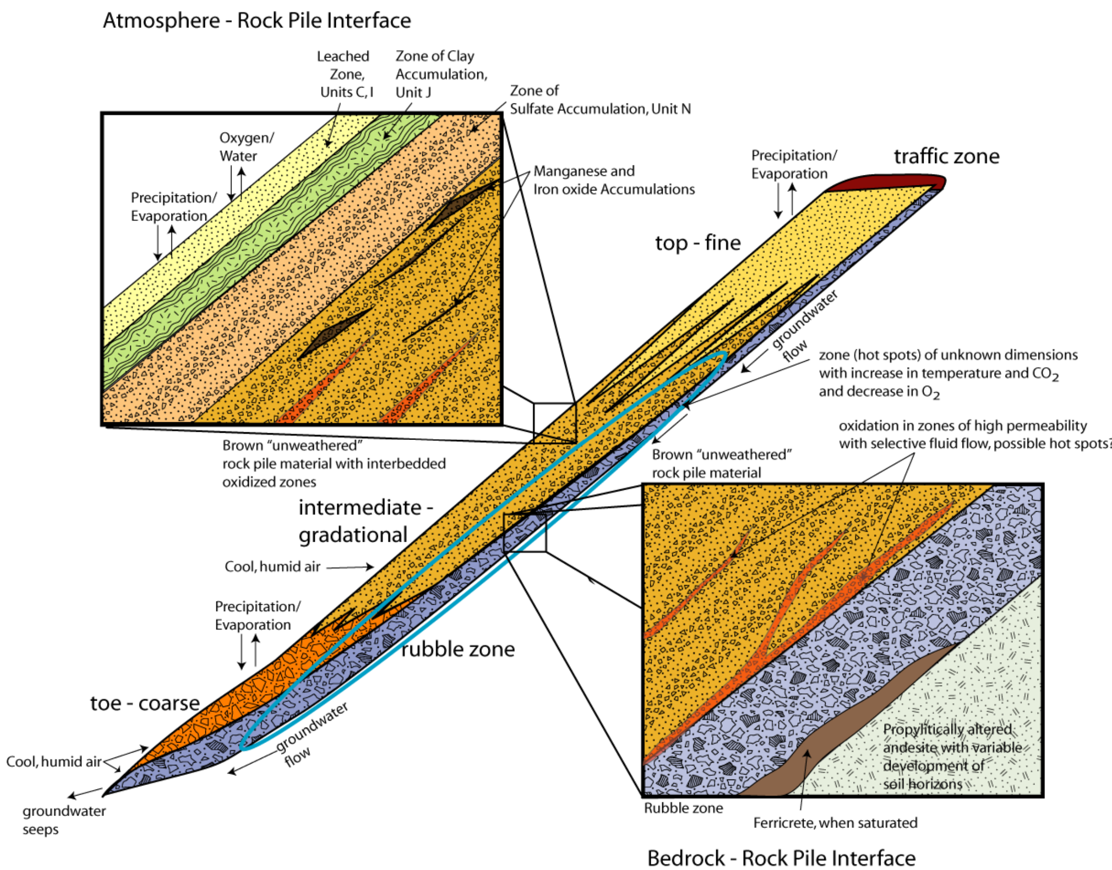

FIGURE 5. Conceptual geochemical weathering model of the Questa rock piles (from field studies at GHN and from Nichols, 1987). See text and McLemore et al. (2005) for explanation of zones and processes. The ground water indicated in the figure is from perched zones not from the local ground water table.

5. STATUS OF COMPONENT INVESTIGATION

The evidence for weathering in the GHN rock pile includes (McLemore et al., 2008a):

- Change in color from darker brown and gray in less weathered samples (original color of igneous rocks) to yellow to white to light gray in the weathered samples (DRA-27; McLemore et al., 2008a, fig. 28-30, 39-42).
- Thin yellow to orange, "burnt" layers within the interior of GHN, where water and/or air flowed and oxidized the rock pile material (DRA-7; McLemore et al., 2008a).
- Paste pH, in general, is low in oxidized, weathered samples and paste pH is higher in less weathered samples (McLemore et al., 2008a, fig. 93).
- Presence of gypsum, jarosite, iron oxide minerals and Fe soluble salts (often as cementing minerals), and low abundance to absence of calcite, pyrite, and epidote in weathered samples (McLemore et al., 2008a, figs. 64, 65-68).

- Tarnish or coatings of pyrite surfaces within weathered samples (McLemore et al., 2008a, figs. 58, 59).
- Dissolution textures of minerals (skeletal, boxwork, honeycomb, increase in pore spaces, fractures, change in mineral shape, accordion-like structures, loss of interlocking textures, pits, etching) within weathered samples (McLemore et al., 2008a, figs. 55, 56, McLemore et al., 2008c).
- Chemical analyses of water samples characterized by acidic, high sulfate, high TDS, and high metal concentrations (Al, Ca, Mg, Fe, Mn, SO_4, McLemore et al., 2008a, table 42).

The chemical analyses of water samples collected from seeps at the toe of GHN before reclamation are characterized by high acidity (low pH), high sulfate, high TDS (total dissolved solids), and high metal concentrations (McLemore et al., 2008b). Sulfate and F are the predominant anions and Al, Ca, Mg, Fe, and Mn are the predominant cations. These components in the aqueous phase are products of weathering within the rock pile. The chemical analyses of the GHN waters reflect the dissolution of calcite, gypsum, pyrite and possible various silicate minerals (McLemore et al., 2008a).

The peak friction angle for GHN samples run at NMIMT vary from 39° to 48° with ultimate (residual) friction angles ranging from 33° to 45° (McLemore et al., 2008a, table 39; DRA-42). These high values of peak friction angle are attributed mostly to grain shape (subangular to very angular) and relative density of the test samples. Samples from unit I of GHN rock pile (φ=42.1°) have the lowest average peak friction angle (McLemore et al. 2008a, table 39; fig. 123). Unit I is near the surface and has been exposed to more intensive weathering, which resulted in a lower point load strength (1.1 MPa) and slake durability index of the rock fragments (87.9%) in some but not all samples of this unit (Tables 37-38). These samples with low slake durability and point load indices also show textural and compositional changes indicative of weathering (McLemore et al., 2008a).

Comparisons between peak friction angle and various geotechnical properties do show some correlations. Specifically, as the percent fines increased, the peak friction angle decreased (McLemore et al., 2008a, fig. 123). This has been documented in previous investigations at Questa (Norwest Corporation, 2005). Also as expected, the peak friction angle decreases with increase in plasticity index, for the GHN samples (McLemore et al., 2008a, fig. 123). The trends between peak friction angle, slake durability, and point load indices are not strong, but in general, the lower friction angles correspond to the lower slake durability and point load indices (McLemore et al., 2008a, fig. 123).

There is no correlation between peak friction angle and lithology (McLemore et al., 2008a, fig. 124). However, a weak negative trend exists between friction angle and QSP alteration (McLemore et al., 2008a, fig. 124). This is attributed, in part, to an increase in the clay mineral sericite (illite), which is associated with QSP alteration. Samples with lower amounts of propyllitic alteration tend to have lower friction angles (McLemore et al., 2008a, fig. 124). But these differences in friction angles are small.

The peak friction angles are quite high for samples from GHN. The lower friction angles are, in general, from the outer part of the rock pile (more weathered), more weathered samples in the interior, and the foundation soils beneath GHN (McLemore et al., 2008a, fig. 125, table 32). This supports previous suggestions and other studies where friction angle decreased with increase in weathering (Arel and Tuğrul, 2001; Bryant, 2003; Tuğrul and Gürpinar, 1997; Moon and Jayawardane, 2004). However, the differences in friction angle between the outer and interior units are relatively small (DRA-42). These results and other studies suggest that changes in physical properties (i.e. particle size, texture and fabric) have a larger effect on the friction angle than do mineralogic and chemical changes (Arel and Tuğrul, 2001; Moon and Jayawardane, 2004).

6. RELIABILITY ANALYSIS

Only the upper third of the GHN rock pile was trenched, mapped, and sampled in detail, although three drill holes also were drilled into the rock pile (Fig. 1). These 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 and the changes due to hydrothermal alteration are more pronounced than those due to weathering.

Samples collected are complete, comparable, and representative of the GHN rock pile at the defined scale. Precision and accuracy are measured differently for each field and laboratory analysis (parameter), and are explained in the project reports, SOPs, McLemore and Frey (2008), and summarized in DRA-0. Most laboratory analyses depend upon certified reference standards and duplicate and triplicate analyses, as defined in the project SOPs.

The sampling and analysis plans for each segment of the field program and the control of accuracy and precision as defined in the SOPs, provides a large high-quality set of observations and measurements that are adequate to support the interpretations and conclusions of this DRA.

The chemical analyses are accurate to within ±5% as determined by duplicate and triplicate analyses and comparison to known internal standards. The mineralogical analyses are estimated to be accurate to within ±10% of the reported value and compare well with other mineralogical techniques (McLemore et al., 2009; DRA 5). See McLemore and Frey (2008) for more details on the quality control and quality assurance, precision and accuracy data. The quantitative mineralogy method obtained by the modified ModAn method is a reliable method that is consistent with the petrographic observations, electron microprobe analysis, clay mineral analysis, and the whole-rock chemistry of the samples. Because it does quantify specific clay and sulfate minerals, both of which are important for understanding the rock and mineral weathering of the Questa materials, bulk mineralogy obtained by this method provides a more reliable mineral composition. In additional, the method reduces the bias associated with petrographic analysis by different petrographers (McLemore et al., 2009; DRA 5).

7. CONCLUSION OF THE COMPONENT

Weathering (which is expressed in these rocks as sulfide oxidation and a consistent suite of rapid reactions between the acidity released by the pyrite oxidation and alkaline minerals, especially calcite) decreased from the outer edge of the rock pile to its interior and then increased toward the base of the rock pile. Weathering also occurs in layers within the interior portions of the rock pile where water and/or air flowed. Oxygen and water are available at and near the surface of the rock piles, at and near the base of the rock pile, in permeable strata within the rock pile, and along cracks and crevasses cutting across the strata that have been formed by slope movement and possibly other means. Clays observed in the rock fragments and soil matrix of the Questa rock piles are not being generated by weathering in the rock pile, but rather were formed by hydrothermal alteration of the rocks before mining (DRA-3). Electron microprobe work, mineralogy and chemistry changes within GHN, and chemistry of waters draining from the rock pile have established that incongruent (residue remains of partially dissolved minerals or new phase forms of gypsum and jarosite; McLemore et al., 2008c, figs. 10, 13, 15) and congruent (dissolution) mineral dissolution have occurred. The geologic data have been assembled into the physical/geologic framework for a conceptual model of a layered rock pile undergoing active chemical and physical weathering.

Friction angle, point load strength index and slake durability index of the GHN rock pile samples decreased as the degree of weathering increased in some samples but not all (McLemore et al., 2008a, figs. 125, 117, 120). However, the decreases were still quite small (DRA-42) and suggest that 25-40 years of weathering have not substantially affected the shear strength properties of these rock pile materials. Comparison of slake durability and point load indices of fragments in the rock pile to values of unweathered drill cores with similar lithologies show that rock fragments in the GHN rock pile have not experienced considerable weathering after emplacement. Therefore, lower values of friction angle, point load strength index and slake durability index of samples from the outer edge of the pile are likely due to post-deposition oxidation, which is consistent with the change in color, loss or obscuring of original igneous texture on the edges and within many rock fragment grains, and increase in weathered mineral products (i.e. gypsum, jarosite). Conversely, the point load strength index and slake durability index values of samples on the interior of the pile are similar to the values of un-weathered drill core samples. Consequently, the samples from the interior of the GHN rock pile are not measurably more weathered since its emplacement. However, the differences in friction angle between the outer and interior units are relatively small (DRA-42, 43, 46, 50). These and other studies suggest that changes in physical properties (i.e. particle size, texture and fabric) have a larger effect than mineralogic and chemical changes on the friction angle than do mineralogic and chemical changes (DRA-42, which is consistent with other studies (Arel and Tuğrul, 2001; Moon and Jayawardane, 2004). The shear strength would be expected to increase with increase in cementation; gypsum, jarosite, and other salts control cementation in the short term. These less stable minerals (geochemically) could form the building blocks (sites) for further stronger cementation consisting of hematite and goethite. Collectively, these results suggest that future weathering will not substantially decrease the friction angle of the rock piles with time.

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9. TECHNICAL APPENDICES

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APPENDIX 1. Descriptions of geologic units at GHN. No relative age relationships could be determined between surface units A-H. GHN rock-pile material consisted primarily of hydrothermally altered andesite and rhyolite (Amalia Tuff) rock fragments.

Geologic Unit in this report	Description	Structure	Lithology	Location
Surface units				
A	Light brown unit with approximately 60% covered by cobbles or larger sized rocks with vegetation growing upon the surface.	Layered in some of the rills near the base.	mixed volcanic rocks	Southern-most surface unit of the stable part
B	Massive, light brown to gray to yellow-brown unit containing crusts of soluble acid salts. Approximately 65% is covered by cobbles or larger sized rocks. Consists of clayey sand with gravel and cobbles and is locally cohesive.	Shallow rills (0.2-1 m deep) of finer grained material are cut into the surface.	quartz-sericite-pyrite (QSP) altered Rhyolite (Amalia Tuff) (70%) and andesite (30%)	Surface unit of stable portion of the GHN rock pile
C	Grayish-brown to yellowish-gray unit consisting of fine-grained materials (sand with cobbles and gravel) and approximately 15% boulders. Locally is cohesive and well cemented by clays and soluble minerals.	Massive alternating zones, up to 10 ft thick.	rhyolite (Amalia Tuff) (70%) and andesite (30%)	Surface unit of stable portion of the GHN rock pile
D	Yellow-brown gravely sand unit that differs from Unit C by a marked increase in cobbles and boulders (approximately 30-40%).	Massive	rhyolite (Amalia Tuff) (80%) and andesite (20%)	Surface unit of unstable portion of the GHN rock pile
E	Orange-brown unit with patches of gray sandy clay containing approximately 15% cobbles and boulders.	Massive	70 % moderate to strong QSP altered rhyolite (Amalia Tuff) and 30% weakly altered Rhyolite (Amalia Tuff)	Surface unit of unstable portion of the GHN rock pile
F	Similar to Unit A, consists of dark brown, silty sand with some gravel.	Massive	andesite	Surface unit of unstable portion of the GHN rock pile
G	Orange-brown to yellow-brown sandy gravel with some cobbles, includes colluvium material.	Massive	andesite	Surface unit of unstable portion of the GHN rock pile
H	Dark gray to red-brown V-shaped unit with oxidized orange zones and consists of poorly sorted, well graded, weakly cemented, gravel sand with some fine sand to fine sand with clay and contains approximately 80% cobbles or boulders.	Massive	andesite	Surface unit at the top of stable portion of the GHN rock pile
Outer, oxidized zone				
I	Light-gray, poorly sorted, well graded clayey to sandy gravel, medium hard with weak cementation, and no plasticity. The matrix is locally sandy clay with medium to high plasticity. The unit is less cemented and finer grained than the overlying unit C.	Overlain by Unit C, up to 10 ft thick	andesite and rhyolite (Amalia Tuff)	Subsurface oxidized unit of stable portion of the GHN rock pile
J	Dark orange-brown, poorly sorted, well graded coarse gravel with clay	Overlain by unit I, 3-12 ft	primarily andesite	Subsurface oxidized unit of stable portion

Geologic Unit in this report	Description	Structure	Lithology	Location
	matrix and weak cementation. The top of the unit locally is a bright orange oxidized layer, 2-4 inches thick.	thick		of the GHN rock pile
Interior zones				
N	Light to dark brown moderately sorted, uniformly graded, moderately hard sandy clay with cobbles, with moderate to high plasticity and well cemented by clay; contains zones of bright orange to punky yellow oxidized sandy clay.	Heterogeneous with numerous coarse and fine layers, 5-10 ft thick	andesite and rhyolite (Amalia Tuff)	Subsurface unit of stable portion of the GHN rock pile
K	Distinctive purplish-brown gravelly sand with cobbles and is weakly cemented and very coarse containing almost no clay. Cobble layer is locally overlain and underlain by finer gravelly sand layers; contacts are gradational.	grades into Unit O, 0-4 ft thick	primarily andesite	Subsurface unit of stable portion of the GHN rock pile
L	Brown-gray, poorly sorted, well graded gravelly sand with cobbles.	Grades into Unit O	andesite	Subsurface unit of stable portion of the GHN rock pile
O	Brown, poorly sorted, sandy gravel matrix in coarse gravel and cobbles. Numerous coarse and fine layers at varying dips and thicknesses appear in the mass of the unit. The unit has cobbles and clay layers, is deformed and heterogeneous, with numerous S-shaped clay lenses and coarse layers.	Variable dip of individual beds	primarily andesite	Subsurface unit of stable portion of the GHN rock pile
M	Orange-brown to brown, poorly sorted, well graded sandy gravel with boulders (up to 1 m diameter). Sandy gravel forms a matrix between boulders and cobbles. The fines are generally gritty.	Unit locally flattens with 20 degree dip	andesite and rhyolite (Amalia Tuff)	Subsurface unit of stable portion of the GHN rock pile
P	Dark brown, poorly sorted, well graded, sandy gravel with medium hardness and no to weak cementation	Pinches out, 0-3 ft thick	andesite	Subsurface unit of stable portion of the GHN rock pile
Q	Dark brown, poorly sorted, well graded, sandy gravel with cobbles with medium hardness and no to minor cementation.	Steeply dipping	andesite	Subsurface unit of stable portion of the GHN rock pile
R	Orange-gray, poorly sorted, well graded sandy gravel to gravel with cobbles with moderate to weak cementation by clay.	Pinches out, 0-3 ft thick	primarily andesite	Subsurface unit of stable portion of the GHN rock pile
S	Dark gray, poorly sorted, well graded sandy silt with no cementation or plasticity.	Pinches out, 0-4 ft thick	primarily andesite	Subsurface unit of stable portion of the GHN rock pile
T	Dark gray, poorly sorted, well graded sandy gravel.		andesite	Subsurface unit of stable portion of the GHN rock pile
U	Brown poorly sorted well graded, sandy gravel with cobbles.	Pinches out, 0-2 ft thick	andesite	Subsurface unit of stable portion of the GHN rock pile
V	Gray to brown-gray, poorly sorted, sandy gravel.	Pinches out, 0-10 ft thick	andesite	Subsurface unit of stable portion of the

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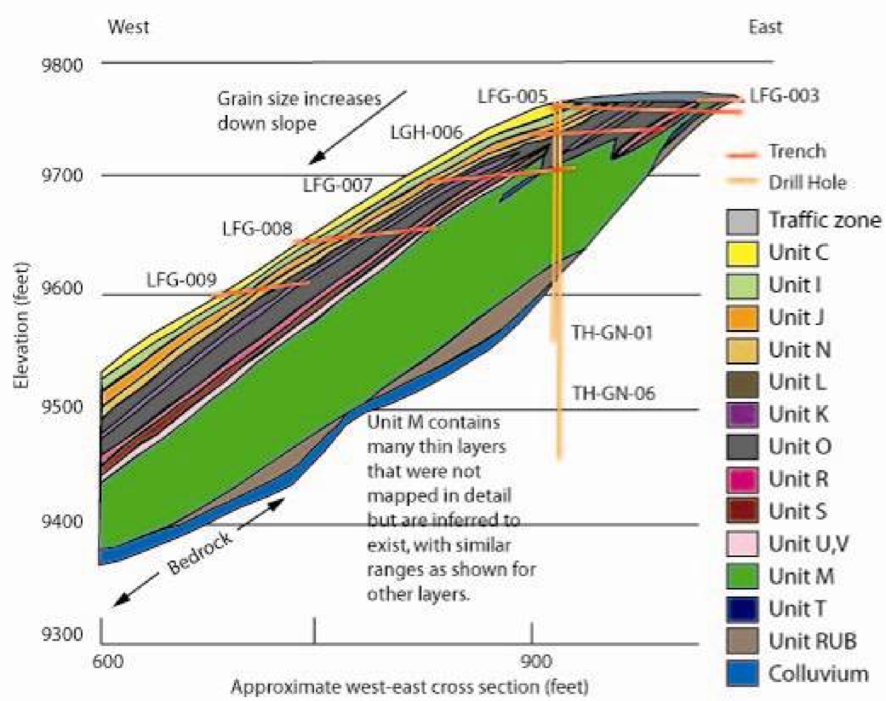
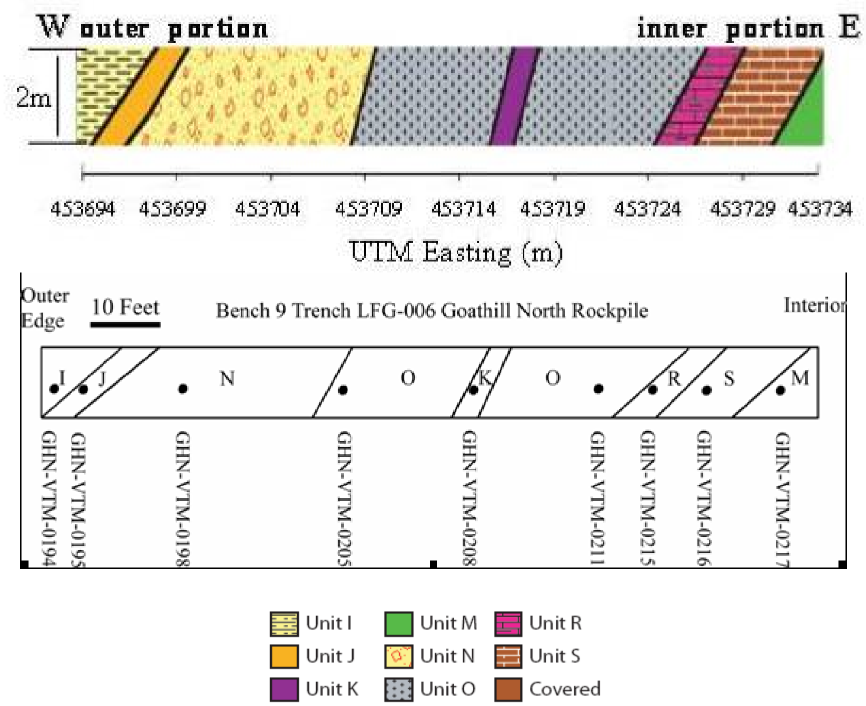
Geologic Unit in this report	Description	Structure	Lithology	Location
				GHN rock pile
W	Olive gray clay zone, similar and possibly correlated to Unit S.		andesite	Subsurface unit of stable portion of the GHN rock pile
rubble zone	Orange-brown, angular cobbles and large boulders (15 cm in diameter) with little sand or clay, cobble-supported rubble zone. Unconformably on top of either soil developed on weathered andesite or colluvium that is similar to the alteration scars.	Unconformable, up to 7 ft thick	andesite, rhyolite (Amalia Tuff)	Basal subsurface unit of stable portion of the GHN rock pile
Shear zone, alluvium, colluvium	Dark gray to brown clayey soil developed on weathered andesite or a yellow to orange brown clay to sandy clay colluvium that is similar to the alteration scars.	1-3 ft thick	andesite	Original surface, material beneath the rubble zone
bedrock	Gray to dark gray to greenish gray, porphyritic to fine-grained andesite.	Locally fractured	andesite	Original andesite bedrock beneath the soil, alluvium, colluvium

APPENDIX 2. Detailed geologic cross section of the upper portion of the stable portion of GHN rock pile (based on mapping of the drill holes and trenches, upper third of the rock pile). Units are described in Appendix 1.



Geologic cross section of the Goathill North rock pile before reclamation (based on color, partical size, texture, lithology, and stratigraphic position)

Note that the surface angle of the rock pile is not 37 degrees because of erosion and compaction.



Geologic cross section of bench 9, trench LFG-006. Note that not all 18 geologic units are present in this bench. Note the vertical exaggeration; actual dips of strata were 20°-40°.

APPENDIX 3. Location of samples (surface, drill holes and trenches) in GHN rock pile as shown in Figure 1.

Drill hole or trench	Samples
TH-GN-01	GHN-ACT-0001 through GHN-ACT-0032
GHN-SI-30	GHN-PXW-0001 through GHN-PXW-0016
LFG-003	GHN-HRS-0001, 2, GHN-LFG-0018 through GHN-LFG-0024, 41
LFG-004	GHN-LFG-0037
LFG-005	GHN-LFG-0085 through GHN-LFG-0090, GHN-VTM-0035-GHN-VTM-0040 through GHN-VTM-0120
LFG-006	GHN-KMD-0013 though GHN-KMD-0027, GHN-VTM-0168 through GHN-VTM-0217
LFG-007	GHN-KMD-0048 through GHN-KMD-0065, GHN-VTM-0231 through GHN-VTM-0303
LFG-008	GHN-KMD-0072 through GHN-KMD-0100, GHN-VTM-0353 through GHN-VTM-0361
LFG-009	GHN-JRM-0001 through GHN-JRM-0027, GHN-VTM-0404 through GHN-VTM-0455
Traffic zone (top of	GHN-LFG-0018, 20, GHN-VTM-0053

Drill hole or trench	Samples
GHN)	
Rubble zone	GHN-VTM-0598, 0607, 0624, GHN-EHP-0003, GHN-ACT-0023 through GHN-ACT-0032, GHN-LFG-0041, 57, 60, 89
colluvium	GHN-ACT-0033, 34, GHN-EHP-0004, 5, GHN-HRS-0095, 96, GHN-LFG-0001 through GHN-LFG-0006, 91, GHN-SAW-0200, 201, GHN-VTM-0500 through GHN-VTM-0502, 506, 507, 508, 509, 510, 553, 605, 606, 611 through 614
Surface samples	GHN-STM-0001 through GHN-STM-0005
Unstable GHN	GHN-EHP-0001, 2, GHN-HRS-0088 through GHN-HRS-0094, GHN-JRM-0037 through GHN-JRM-0047, GHN-SAW-0002 through GHN-SAW-0005m GHN-VTM-0003