CHARACTERIZATION OF GOATHILL NORTH MINE ROCK PILE, QUESTA MOLYBDENUM MINE, QUESTA, NEW MEXICO[1]

Virginia T. McLemore[2], Kelly M. Donahue, Erin Phillips, Nelia Dunbar, Patrick Walsh, Luiza A. F. Gutierrez, Samuel Tachie-Menson, Heather R. Shannon, Virgil W. Lueth, Andrew R. Campbell, G. Ward Wilson, and Bruce M. Walker

Abstract. Rarely do rock pile characterization methods allow for examination and sampling of the interior of large rock piles *in-situ*. The regrading of the Goathill North (GHN) rock pile at the Questa mine provided a unique opportunity to examine and sample the interior of a large rock pile through the construction of trenches cut into the rock pile as earth-moving progressed. Maps of each bench were created to document the different stratigraphic units, including the thickness, dip, and extent of the units. Units were defined based on grain size, color, and other physical properties. Units were correlated between benches and downward through the series of successively excavated trenches. Typically, paste pH increased with distance from the outer, oxidized zone (west) towards the interior units (east) of the GHN rock pile. The outer zone was oxidized (weathered) based upon the white and yellow coloring, low paste pH, presence of jarosite and gypsum, and absence of calcite. However, the oxidation/reduction (weathering) state in the interior zone is not yet determined. The base of the rock pile closest to the bedrock/colluvium surface represents the oldest part of the rock pile since it was laid down first. Portions of the base appeared to be nearly or as oxidized (weathered) as the outer, oxidized zone, suggesting that air and water flow along the basal interface occurred and possibly was an active weathering zone. Analyses of samples from unweathered, unoxidized drill core samples and from the GHN rock pile are similar in clay mineralogy as determined by XRD and electron microprobe analyses, which suggests that the majority of clay minerals in the GHN samples were derived from the original, pre-mined hydrothermal alteration and not post-mining weathering.

Additional Key Words: mineral weathering, acid drainage, oxidation of rock piles, stability, mine waste rock

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[2] Virginia T. McLemore, PhD, Senior Economic Geologist/Minerals Outreach Liaison, New Mexico Bureau of Geology and Mineral Resources (NMBGMR), New Mexico Institute of Mining and Technology (NMIMT), Socorro, NM 87801, ginger@gis.nmt.edu. Kelly Donahue, Erin Phillips, Patrick Walsh, Geological Associates, NMBGMR. Nelia Dunbar, PhD, Assistant Director/Geochemist, and Virgil Lueth, PhD, Mineralogist/Economic Geologist, NMBGMR. Luiza Gutierrez, Samuel Tachie-Menson, Heather Shannon, graduate students, NMIMT. Andrew Campbell, PhD, Professor, Earth and Environmental Science Dept, NMIMT. G. Ward Wilson, PhD, Professor, Engineering Geology, University of British Columbia, Vancouver, Canada. Bruce M. Walker, PhD, mine geologist, Molycorp, Inc., Questa, N.M.

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Introduction

Purpose

Rock piles, the preferred term by many in the metal mining industry today, refer to the man-made structures consisting of piles of non-ore material that had to be removed in order to extract the ore. This material, referred to as mine waste, overburden, subore, or proto-ore in older literature, does not include the tailings material, which consists of non-ore material remaining after milling.

Geologic, mineralogical, geochemical, geotechnical, and hydrologic characterization of mine rock piles with depth is important to characterize pre-mining background conditions (Briggs et al., 2003), to characterize and predict stability and erosion (Dawson, 1994; URS Corporation, 2000), to predict acid-rock drainage (McLemore et al., 2004b, Shaw et al., 2002), to properly dispose of and manage mine overburden (Dawson, 1994), and to develop mine closure plans (URS Corporation, 2000; Wels et al., 2002). Most site characterizations of rock piles are based upon drilling of the rock piles (Robertson GeoConsultants, Inc. 2000a, b; URS Corporation, 2000), shallow surface test pits (URS Corporation, 2000), or composite surface sampling (Smith et al., 2000a, b; Munroe and McLemore, 1999, 2000; Briggs et al., 2003; Wildeman, 2003). Rarely do these methods of site characterization allow for examination, mapping, and sampling of the interior of large rock piles *in-situ*. Examination of the interior of two mine rock piles during removal was described by Fines et al. (2003) and Tran et al. (2003) who revealed complex dipping layers within the rock piles. Most other studies of mine rock piles involved drilling, surface test pits, and numerical modeling.

The regrading of the Goathill North (GHN) rock pile at the Molycorp Questa molybdenum mine, New Mexico provided a unique opportunity to examine, map, sample, and develop a conceptual model of the interior of a large mine rock pile *in situ* through the construction of trenches cut into the rock pile. The purpose of this report is to describe the mapping and sampling procedures and preliminary laboratory results of trenching within the interior of the GHN rock pile. Geologic mapping of the GHN rock pile using surface mapping, trench mapping, and correlations with drill holes is important to provide a stratigraphic and structural framework for the sampling and modeling of the rock pile. The geologic mapping techniques employed in this study differ from most studies because of the construction of wide trenches with four benches downward through the rock pile as regrading progressed (McLemore et al., 2005).

Investigation approach

The purpose of the Molycorp study is to develop a model to identify and assess conditions and processes occurring in the rock piles, especially related to the physical and chemical weathering of rock pile materials at the Questa mine. A key component of this investigation is to estimate what changes in these materials, if any, have occurred since construction of the rock piles, and thereby develop a model to extrapolate what future changes could occur. As a result, it should be possible to determine the effect of weathering on the geotechnical behavior of the rock piles as a function of time and degree of weathering. The current approach is to test the laboratory geotechnical behavior of samples across a range of weathering states that are defined by petrology, mineralogy, and chemistry for samples collected from the existing rock piles and elsewhere in the Questa-Red River area.

The first step in understanding the contribution of weathering to the long-term stability of the Questa mine rock piles is to collect and compile data from physical, mineralogical, chemical, and geotechnical characterization of samples of earth materials contained in nine rock piles at the site. McLemore et al. (2005) addressed the mapping, sampling, and preliminary laboratory results of trenching activities of GHN rock pile in 2004-2005. This report will present new petrographic, mineralogical, and chemical results.

Description of site

The Questa molybdenum mine is located on the western slope of the Taos Range of the Sangre de Cristo Mountains, Taos County in northern New Mexico (Fig. 1). The mine is on southward facing slopes and is bounded on the south by Red River and on the north by mountain divides. The geology and mining history of the area is complex and described by others (Carpenter, 1968; Clark, 1968; Lipman and Reed, 1989; Meyer and Leonardson, 1990; Czamanske et al., 1990; Roberts et al., 1990; Meyer, 1991; Meyer and Foland, 1991; Robertson GeoConsultants, Inc. 2000a, b; Ross et al., 2002; Rowe, 2005). Lithologies likewise are diverse, ranging from metamorphic to volcanic rocks to granites to shales, limestones, and sandstones.

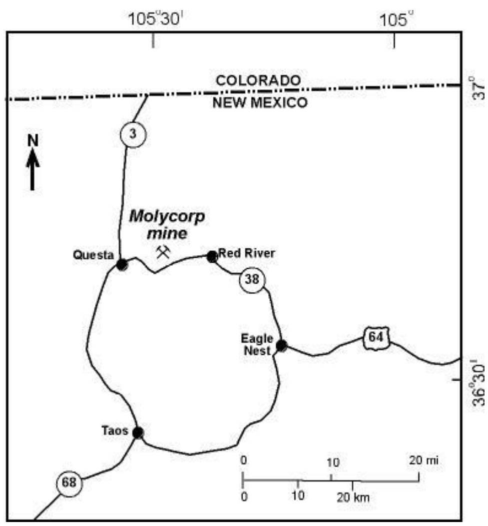

Figure 1. Location of Molycorp Questa mine, northern Taos County, New Mexico.

The mine began production in 1918 from underground workings. Open-pit removal of overburden began in 1964; ore production began in 1965 and ended in 1982, at which time approximately 73.5 million metric tons of ore with an average grade of 0.185% MoS_2 had been processed (Schilling, 1960, 1990; Ross et al., 2002; McLemore and Mullen, 2004). Underground mining resumed in 1982 and used block caving mining methods to extract the molybdenum (Mo) ore. During the open-pit period of mining, approximately 317.5 million metric tons of overburden rock were stripped and deposited onto mountain slopes forming the rock piles examined in this study (URS Corporation, 2000). The elevation of these rock piles ranges from 2301 to 3020 m.

The GHN rock pile is one of nine rock piles created during open-pit mining and contained approximately 10.6 million metric tons of overburden rock material with slopes similar to the original topography. GHN was comprised of two areas: a stable area and an unstable area

(Fig. 2). Molycorp stabilized this rock pile by removing material off the top portion of both areas to create a buttress at the bottom of the pile, decrease the slope and reduce the load (Norwest Corporation, 2003). During the progressive regrading of the top of GHN (regrading), trenches were constructed to examine, map, and sample the internal geology of the rock pile.

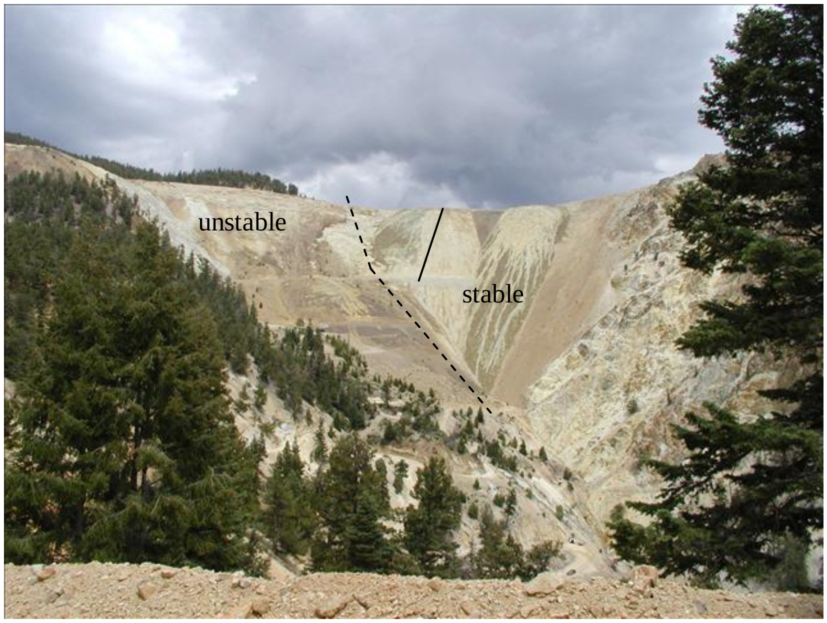

Figure 2. GHN before regrading, looking east. Solid line indicates approximate location of trenches in summer-fall 2004; dashed line indicates the boundary between the stable and unstable portions of the rock pile.

There are basically five methods of construction of mine rock piles (Nichols, 1987; Quine, 1993; Shum, 1999):

1. End dumping (dumping rock over dump face resulting in particle size increasing down slope towards the toe of the rock pile)
2. Push dumping (dumping from trucks then leveling/pushing by tractor and shovel resulting in little particle size segregation at top, coarse particle sizes at toe)
3. Free dumping (dumping in small piles on the surface of the rock pile, grading the material, and compacting in layers or lifts resulting in dense, no real particle size segregation)
4. Drag-line spoiling (deposited on surface without construction of lifts and minimal compaction resulting in dense, no real particle size segregation)
5. Mixing of waste rock with tailings.

The Questa rock piles were constructed primarily by haul truck end dumping in high, single lifts, which involves the dumping of rock over the edge of the hill slopes (URS Corporation, 2000; McLemore et al, 2005). End dumping generally results in the segregation of materials with the finer-grained material at the top and coarser-grained material at the base

(Fig. 3). The resulting layers are locally at or near the angle of repose and subparallel to the original slope angle. End dumping results in five zones of segregation (Fig. 3; Nichols, 1987; McLemore et al., 2005):

1. Upper traffic surface
2. Top of the rock pile where fines were more concentrated than coarser material
3. Intermediate zone where material is well graded and evenly distributed
4. Toe of the rock pile where mostly coarse material is concentrated
5. Basal rubble zone of cobbles and boulders along the contact between the rock pile and the original bedrock or colluvium.

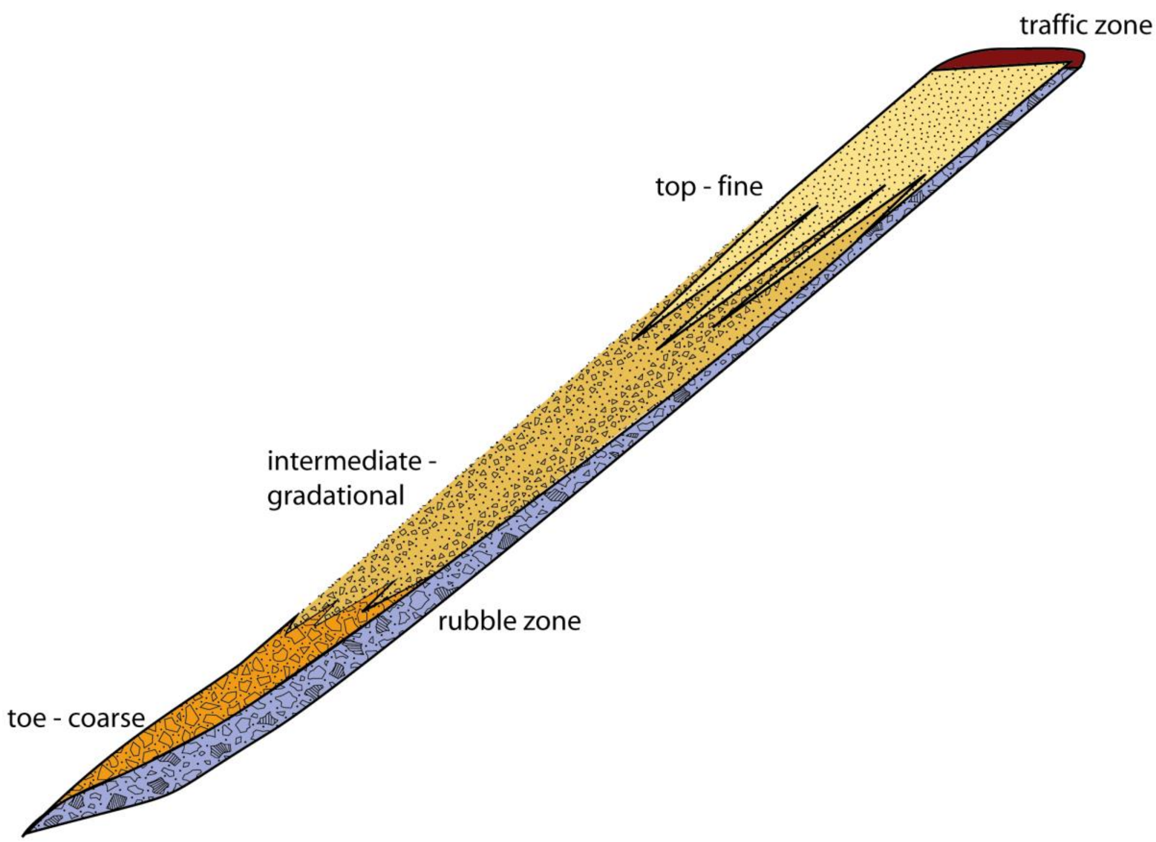

Figure 3. Conceptual model of the Questa rock piles (from field studies at GHN and from Nichols, 1987). See text below and McLemore et al. (2005) for explanation of zones.

Procedures

Mapping procedures

Standard geologic mapping techniques were used in this study (Lahee, 1961; McLemore et al. 2005). Surface units on the rock piles were identified visually, using units defined by Wagner and Harrington (1995) as a guide. Each unit boundary was mapped, using the combined aerial photograph and topographic map provided by Molycorp (McLemore et al., 2005). Remote sensing results by Spectral International, Inc. (unpublished) and Airborne Visible-Infrared Imaging Spectrometer (AVIRIS) data (Livo and Clark, 2002) were incorporated where appropriate. Each unit on the surface and in the subsurface was examined and described, including the dip, strike, and true thickness. The units were differentiated mostly based on color, grain size, composition, texture, stratigraphic position, and other soil properties. Longitudinal sections were made of each bench in the GHN rock pile. The project geologic mapping, work plans and procedures describe the mapping, field and laboratory analysis procedures that were used for this study and are available upon request.

The locations of the trenches to examine the subsurface of GHN as it was exposed during regrading were based upon

1. Surface geologic mapping (McLemore et al., 2005)
2. Location of prior drill holes in the rock pile
3. Geophysical surveys (van Dam et al., 2005)
4. Molycorp mitigation plans (Norwest Corporation, 2003).

Specific location and construction data for each trench is in the project database (McLemore et al., 2004a). Two trenches were constructed in the stable portion of GHN in June 2004 to

1. Train personnel in sampling and mapping procedures
2. Test mapping and sampling procedures
3. Confirm the geophysical studies
4. Provide a base line of the structure and stratigraphy
5. Aid in locating additional trenches.

Starting in September 2004, five additional trenches were constructed during the regrading of the stable portion of GHN rock pile. In February-April 2005, 13 trenches were constructed in the unstable portion of the rock pile. Each trench was surveyed, mapped, and sampled.

Trenches typically had four benches, approximately 1.5 m wide and did not exceed 1.2 m in height, to give an overall slope of 1.4 horizontal to 1.0 vertical within the trench (Fig. 4, 5). Each trench was extended for a length sufficient to explore site conditions, maintain the regraded 2:1 slope, and ensure personnel safety. Several trenches in the unstable portion of GHN consisted of only one or two benches.

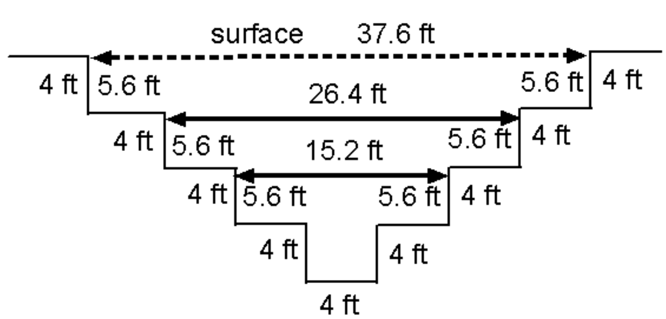

Figure 4. Sketch of a typical trench for the GHN rock pile.

Trench walls and benches were surveyed using a differential global positioning system, NAD 27 CON (Fig. 6). For every trench, geologic maps (Fig. 7) of each trench and lithologic logs of each bench were created to describe the different subsurface mine soil units, including the thickness, dip, stratigraphic position, and spatial extent of the units. Units were correlated between benches and on opposite sides of a trench, and several units were correlated downward through the series of five successively excavated trenches. Eighteen units were differentiated, described and sampled.

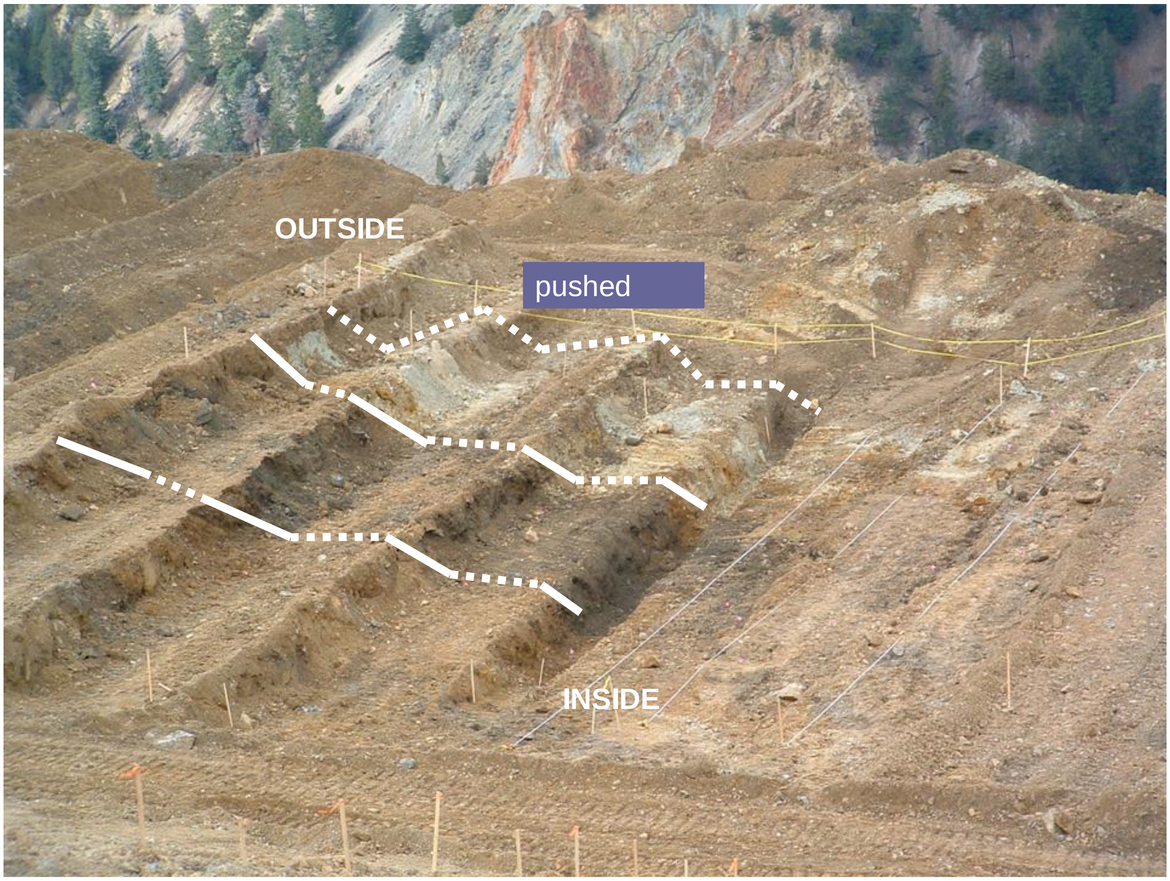

Figure 5. Southwestward view of zonation at outer margin of the GHN rock pile. White zone inside the yellow tape represents outer margin of original dumped pile (pushed material beyond the white zone). Color zones from outer zone to interior pile: Oxidized, leach zone–white to gray to yellow (Unit C, I); oxidized, sulfate accumulation–orange (Unit J); intermediate zone–dark brown (Unit N), internal zones–brown (Units K-W, excluding N). See conceptual model and cross-section given in Fig. 3. Geologic units are described below in Table 2.

<u>Sampling procedures</u>

We employed sampling procedures, descriptions, and analytical analyses typically used for soil profiles because the material in the rock piles can be classified as mine soils (URS Corporation, 2000; Haering et al., 2004; Stormont and Farfan, 2005). *Mine soils* are soils that form from organic matter, mineral soil materials, sediments, and rocks redistributed by humans during or after mining process (Galbraith, 2004).

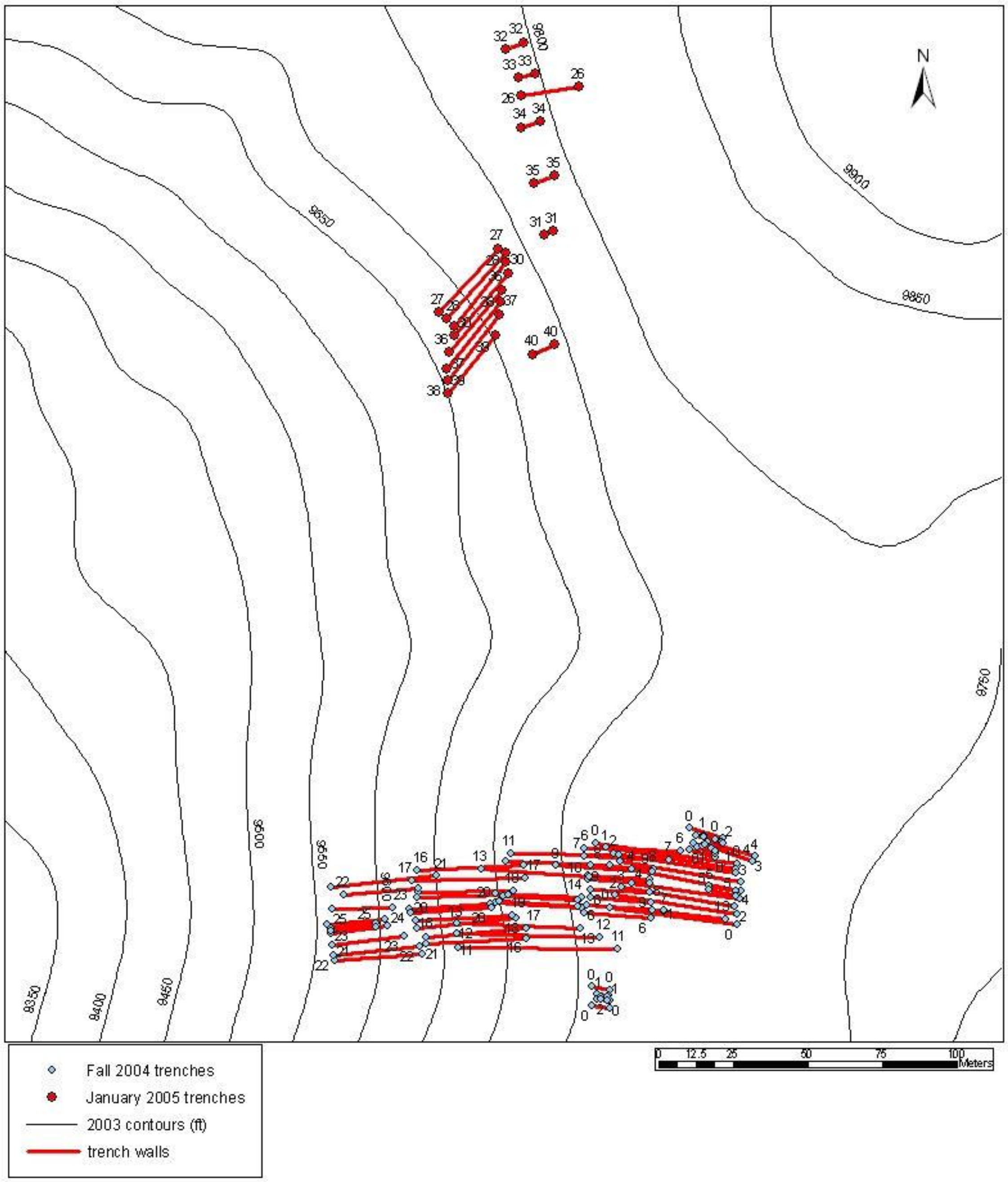

Figure 6. Map showing GHN trench locations. Red lines show trench walls. Circles show surveyed trench corner points. Black lines show elevation contours. Numbers refer to bench numbers.

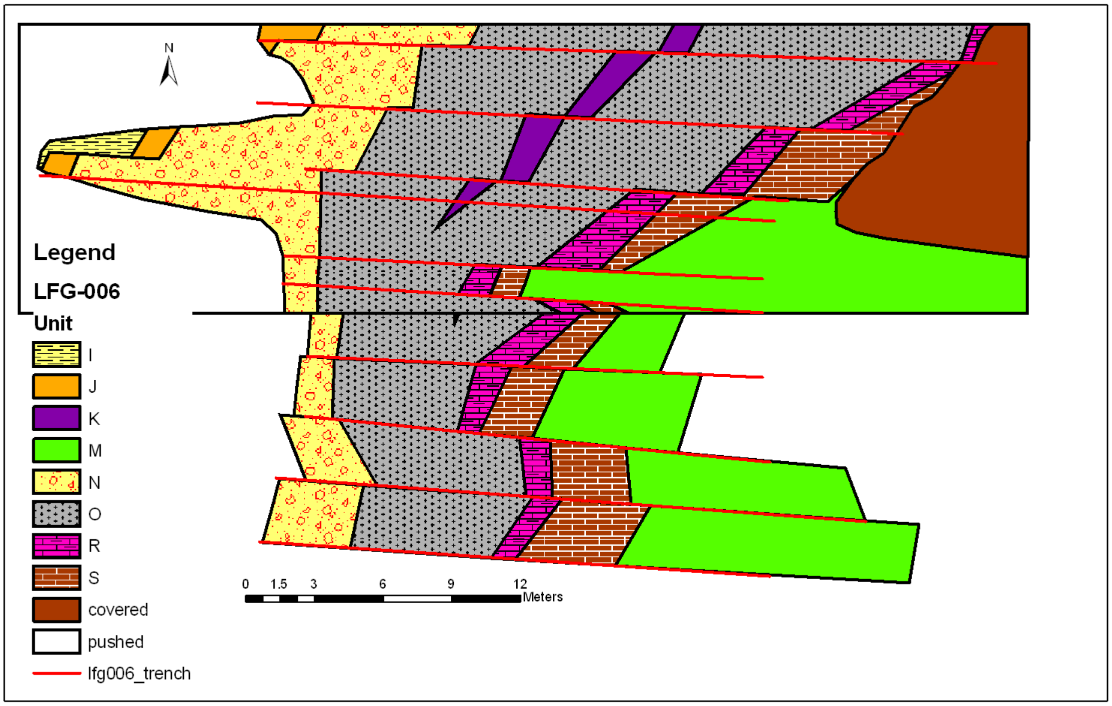

Figure 7. Geologic map of trench LFG-006, stable portion of GHN. Units are described below in Table 2. Offsets show bench wall locations and are not faults. Red lines indicate the edge of each bench. The units closest to the base of the rock pile (east) are older than the younger, overlying units towards the outer edge of the rock pile (west).

During GHN regrading, the field team sampled within each of the subsurface units in the trenches after the unit boundaries were identified. The following *in-situ* measurements were taken along either the horizontal or vertical surfaces of each exposed bench and along the base of the trench, according to ASTM standards (specific procedures are available upon request): sand cone (density), tensiometer (matric suction), moisture content, grain size, infiltration tests, and nuclear gauge measurements (density, moisture content, compaction). Gravimetric water content samples consisting of approximately less than 2 cm diameter material also were collected at the same locations selected for the measurement of *in-situ* matric suction and infiltration tests of undisturbed areas within the trenches. Team members collected samples from each defined unit for geochemical, geotechnical (including shear box tests), biological, isotopic, and electron microprobe analyses. Channel sampling for pyrite modeling was performed along approximate 1.5-m-long horizontal slots using a rock hammer to chip material from bench walls placed into a sample bag. Additional material from selected layers was collected for humidity-cell tests in the future.

<u>Laboratory Procedures</u>

The laboratory tests performed on the samples thus far include gravimetric moisture content and paste pH, conductivity, TDS, petrographic analyses, and clay mineral analyses. The tests were performed at the Mineral Engineering Soils Laboratory and the Bureau of

Geology Clay Laboratory both at New Mexico Tech using laboratory procedures (typically ASTM procedures where appropriate) established as part of the overall project procedures documentation. Petrographic analyses were performed using a binocular microscope with additional microprobe, X-ray diffraction, and whole rock geochemical analyses. Clay mineralogy of major clay mineral groups was performed using standard clay separation techniques and X-ray diffraction analyses of the clay mineral separate on an oriented glass slide (Hall, 2004; Moore and Reynolds, 1989). Clay analyses are reported as parts in ten for the clay fraction to reflect the accuracy of the analyses and do not reflect the amount of clay in the entire sample. Whole-rock geochemical analyses were obtained by X-ray fluorescence spectroscopy at the New Mexico State University and Washington State University laboratories. The geochemical analyses will be presented in a future report; however normative mineral concentrations were calculated using standard CIPW (Cross, Iddings, Pirsson and Washington; Best 1982) techniques for comparison to the modal mineralogies obtained by petrographic techniques.

Description of Goathill North Units

Composition of rock piles based on the material removed from the open pit

The lithologies mined from the open-pit deposit are grouped into five major rock types: rhyolite (Amalia Tuff), andesite breccia, andesite (including latite and quartz latite), granitic porphyry, and aplite. Estimates of the proportions of various lithologies that were mined from the open-pit deposit were determined from mine cross sections (Table 1). Other mine lithologies present in the open-pit deposit included volcaniclastic sandstone, shale, and rhyolite and granitic dikes and were typically included with the andesite breccia or andesite in Table 1. Field and laboratory analyses indicated that the GHN rock pile consisted primarily of andesite and Amalia Tuff rock fragments.

Table 1. Estimates of volume of each lithology mined from the open-pit deposit determined in this study using Molycorp cross sections. These are rough estimates of the volume of each lithology in the rock piles. Explanation of the lithologies and procedures are in McLemore (2005). QSP—quartz-sericite-pyrite hydrothermal alteration, prop—prophylitic hydrothermal alteration.

Symbol	Lithology	Volume percent	Relative estimate of strength (1 strong, 3 weak)	Comments
Tdqpt-Trt	Amalia Tuff	10	1	Mostly QSP altered, no ore
Tanbx	Andesite breccia	14	3 2	50% QSP, 50% prop, no ore
Tanfp	Andesite (including latite and quartz latite)	46	3 2	50% QSP, 50% prop, some ore
Thfp	Christmas Tree porphyry	8	2	QSP altered, no ore, pyrite rich
Tpap	Aplite	22	1	Most of ore from this unit
TOTAL		100		

Description of geologic units in Goathill North

Eighteen lithologic units were mapped and described for each trench and are summarized in Table 2. The surface units are shown in a geologic map of GHN in McLemore et al. (2005).

The contact between the GHN rock pile and bedrock/colluvium has been exposed and examined in various trenches at the top of the stable portion of GHN, in trenches throughout the unstable portion of GHN, and at the toe of GHN. Observations in the various trenches that cut into the base of the rock pile and the bedrock indicated that the basal portion of the GHN rock pile consisted of a cobble-supported rubble zone of gravel through boulder-sized material lying unconformably on top of either 1) a dark gray to brown clayey soil developed on weathered andesite or 2) a yellow to orange brown clay to sandy clay colluvium that is similar to the natural alteration scars found along the Red River valley (Meyer and Leonardson, 1990). The rock pile material observed in trenches in the stable portion of GHN overlaid yellow to orange brown acid-weathered or oxidized soil or colluvium. The rubble zone at the base of the rock pile contained mostly andesite cobbles, jarosite, and gypsum with moderate sorting, and clay to pebble size material that was developed on top of bedrock. The rubble zone increased in thickness towards the base of GHN rock pile.

Table 2. Descriptions of geologic units at GHN. No relative age relationships or thicknesses can be determined between surface units A-H.

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 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.	Amalia Tuff (70%) and andesite (30%)	Surface unit of stable portion of the GHN rock pile

Table 2. continued

Geologic Unit	Description	Structure	Lithology	Location
D	Yellow-brown gravely sand unit that differs from Unit C by a marked increase in cobbles and boulders (approximately 30-40%).	Massive	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 with approximately 15% cobbles and boulders.	Massive	70% moderate to strong QSP altered Amalia Tuff and 30% weakly altered 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, 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 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 matrix and weak cementation. The top of the unit locally is a bright orange oxidized layer, 2-4 inches thick.	Overlain by unit I, 3-12 ft thick	primarily andesite	Subsurface oxidized unit of stable portion 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, zones of bright orange to punky yellow oxidized sandy clay.	Heterogeneous with numerous coarse and fine layers, 5-10 ft thick	andesite and 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, almost no clay. Cobble layer is locally overlain and underlain by finer gravelly sand layers and 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

Table 2. continued

Geologic Unit	Description	Structure	Lithology	Location
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. Heterogeneous, deformed layer 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 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 low 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 medium 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 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 in the upper and middle portions of the rock pile, thickens towards the base of the rock pile	andesite, 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

Results of moisture contents, paste pH, paste conductivity, and paste TDS are presented in Tables 3 and 4. 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% (Table 3). Moisture contents as high as 25.5% are reported in previous studies (URS Corporation, 2000). The average paste pH from the GHN pile was 4.39 (Table 4). In previous studies, paste pH varied from 2.1 to 10, paste conductivity varied from 0.19 to 23,000 ms/cm, and paste TDS varied from 1.9 to 1700 ppm (URS Corporation, 2000). Typically, paste pH increased with distance from the outer, oxidized zone (west) towards the interior zone (east) of the GHN rock pile (Phillips, et al. 2005). The low pH and yellow to orange color is consistent with oxidized conditions along with the presence of jarosite, gypsum, and lack of calcite. Additional laboratory data and interpretations will be in future reports.

Grain size analyses, including hydrometer analyses, were performed on trench samples from GHN. These results showed gravel, sand, and fines varied from 19 to 76.8%, 22.4 to 63.6%, and 0.36 to 17.4%, respectively (Fig. 8). Most of the samples were classified as poorly-graded or well-graded sandy gravel with small percentage of fines.

Table 3. Summary of moisture contents (percent) of samples from GHN by geologic unit (described in Table 2 and McLemore et al., 2005).

Geologic Unit	Average	Maximum	Minimum	Number of samples
Oxidized, outer zone				
C	6.97	9.33	5.48	3
I	15.47	23.89	10.72	5
J	10.39	17.13	6.61	16
Internal zone				
N	13.13	17.25	9.6	17
K	10.16	11.77	8.34	9
L	8.62			1
O	11.2	18.01	6.15	50
M	10.45	15.09	5.54	13
R	10.51	11.46	9.91	3
S	10.43	13.36	7.43	6
U	10.61	13.23	7.99	2
V	9.23	9.6	8.59	3
W	9	9.58	8.41	2
Basal rubble zone	11.23	18.49	7.05	11
Colluvium	13.55	20.78	3.89	10
Weathered bedrock	16.03	18.32	14.01	8

Grain shape and texture were assessed by petrographic methods and the electron microprobe, involving examination of the grain shape and texture of the finer-grained soil component of the samples, as well as of the rock fragments within the rock pile material. For rock pile samples, shapes of clasts were classified based on AGI data sheet 18.1 comparison chart for estimating roundness and sphericity. Based on this classification, sphericity ranged from subprismoidal to subdiscoidal and roundness ranged from very angular to subrounded (project database). Backscattered electron images allow detailed examination of grain shape and texture at small scales. In general, these images revealed a predominance of angular to subangular clasts compared to rounded clasts. The majority of rock pile samples exhibited a clast-supported clay-sized matrix. However, some samples contained abundant clay-size material and are matrix supported. Pyrite where present ranged from cubic to rounded, but usually had somewhat rounded edges.

Table 4. Summary of paste tests by selected geologic unit (updated from McLemore et al., 2005).

Unit	n	Paste pH (standard units)				Paste Conductivity (mS/cm)			
		Min.	Max.	Avg.	Std. dev.	Min.	Max.	Avg.	Std. dev.
Surface units									
D	2	2.87	6.60	4.74	2.64	0.07	0.18	0.13	0.08
E	14	2.45	4.38	3.31	0.68	0.42	5.13	2.17	1.47
G	2	4.27	4.86	4.57	0.42	0.46	1.15	0.81	0.49
H	12	3.15	5.65	4.71	0.74	0.26	3.09	1.44	1.05
Oxidized, outer zone									
C	12	2.33	3.43	2.85	0.35	0.44	4.90	2.25	1.17
I	28	2.19	4.77	3.07	0.69	0.75	6.54	3.20	1.23
J	52	2.14	5.75	3.37	0.75	1.22	12.35	3.53	2.06
Internal zone									
N	58	2.15	4.71	3.39	0.54	1.06	9.97	3.07	1.66
N1	4	3.11	5.06	4.07	0.80	2.41	3.91	3.32	0.66
K	36	2.36	7.20	4.83	1.53	0.58	5.02	2.35	1.12
L	9	2.25	8.74	6.46	2.12	0.96	2.75	2.32	0.60
O	163	2.43	8.98	5.49	1.66	0.18	7.96	2.56	1.42
O1	5	3.35	4.59	3.83	0.47	2.08	4.50	2.93	1.04
M	57	2.41	9.56	4.45	1.21	0.28	4.12	1.74	0.77
R	16	3.17	9.60	6.05	1.98	0.72	3.59	1.68	0.72
S	20	2.61	9.47	6.25	1.87	0.83	3.65	2.00	0.63
T	6	3.95	4.77	4.25	0.31	0.85	2.10	1.42	0.41
U	15	2.45	5.52	3.86	0.90	0.70	4.25	2.22	1.06
V	11	3.37	5.77	4.39	0.61	1.03	3.21	1.65	0.61
W	2	6.62	6.68	6.65	0.04	0.59	0.98	0.79	0.28
Traffic Zone	27	2.84	6.12	4.43	0.91	0.39	3.26	1.90	0.63
Rubble Zone	25	2.39	8.56	3.68	1.31	0.22	6.12	1.64	1.34
Colluvium	10	2.9	5.37	3.43	0.74	1.33	5.05	3.11	1.33
Bedrock	30	1.86	9.60	4.00	1.93	0.44	5.69	2.39	1.34

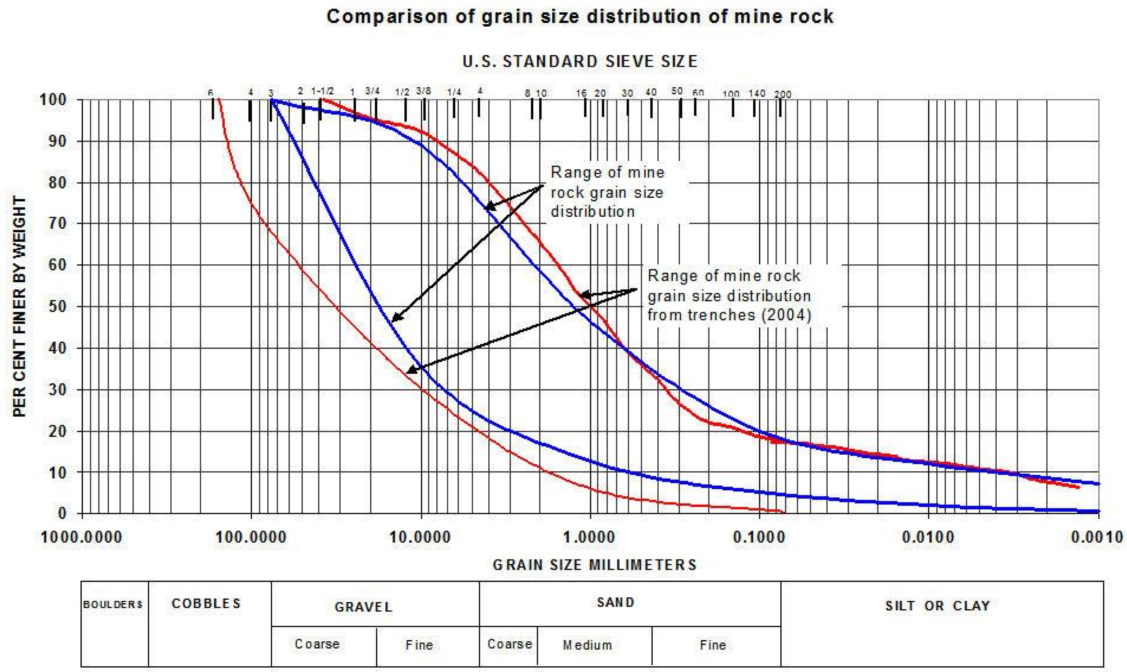

Figure 8. Grain size analyses of selected samples from GHN compared to data contained in earlier Molycorp reports. The red lines are from data in URS Corporation (2000) and the blue lines are from data obtained in this study from GHN.

Petrography And Mineralogy

Petrographic analyses

Petrographic analysis of rock pile material was performed in order to characterize mineralogy, rock fragment lithology, and minerals that are pertinent to the study of weathering. Soil petrography, with the help of electron microprobe, X-ray diffraction, and whole rock geochemical analyses, was used to better understand variations in the original rock pile and identify the potential mineralogical and geochemical effects of weathering. Twenty-one rock pile samples were examined from a traverse along a single bench within a rock pile trench on GHN (Fig. 9). This suite of samples is useful because it provides a profile from the outer, oxidized margin of the rock pile inward, which allows the comparison of rock fragment lithology and mineral abundance. Eight mappable units were identified along this bench. The trench did not expose the basal rubble zone.

Within the population of rock fragments observed in the GHN samples, two main rock types, andesite, and rhyolite (Amalia Tuff) were observed. Both exhibited original igneous textures, although the andesite fragments have typically undergone significant hydrothermal alteration whereas the Amalia Tuff fragments were relatively pristine. The Amalia Tuff fragments consisted of large (~mm size) quartz and feldspar phenocrysts, surrounded by a devitrified glass matrix. The andesitic rock fragments exhibited hydrothermal alteration textures, consisting of fine-grained intergrowth of quartz and potassic feldspar. These rocks also contained dispersed blocky epidote and pyrite crystals. Many of the andesitic rock fragments contained considerable concentrations of clay minerals, mainly replacing original igneous phenocrysts, but also as small pockets within the matrix of the samples. Feldspars in both lithologies were typically partially to completely replaced by clay minerals.

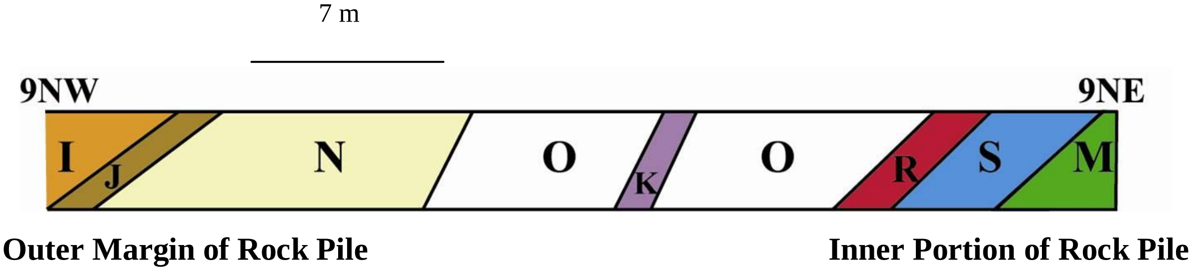

Figure 9. Geologic cross section of bench 9, trench LFG-006. Samples used for petrographic analysis were obtained at approximately 1.5 m intervals. Refer to this figure for subsequent plots.

The composition of rock fragments and the intensity of hydrothermal alteration are characteristics inherent to rock pile material. These features were present in the rocks before they were emplaced in the rock pile. Understanding these characteristics is important in order to obtain baseline conditions from which weathering can be determined. It is possible to recognize some mapped units based on the relative proportions of the two lithologies found within GHN (Fig. 10, Table 2). For example, all samples from unit O contained ≥ 80% andesite rock fragments. Propylitic (chlorite + epidote ± calcite) and QSP (quartz + sericite ± pyrite) were the most common types of hydrothermal alteration found in these samples. The intensities of both types of hydrothermal alteration varied considerably across this bench. QSP hydrothermal alteration intensity appeared to be relatively consistent within mapped units (Fig. 11). In addition, QSP and propylitic hydrothermal alteration intensities were inversely related and samples with the most QSP hydrothermal alteration usually contained a greater proportion of Amalia Tuff (Fig. 12).

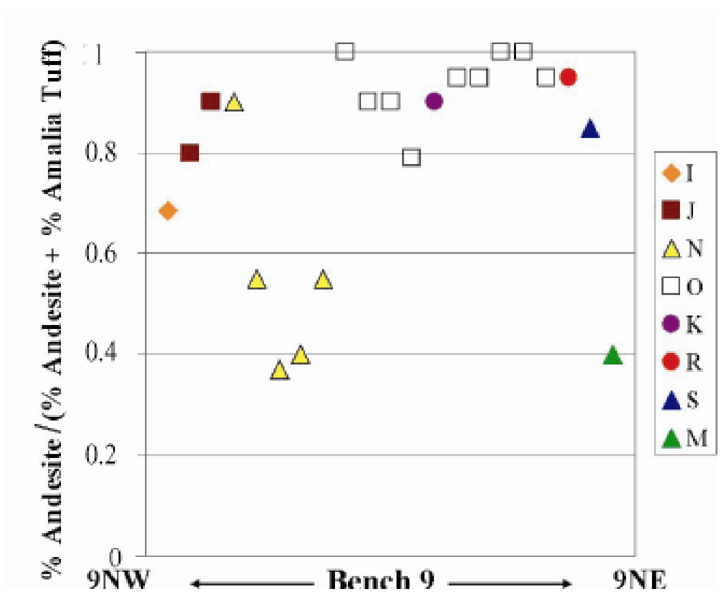

Figure 10. Plot of rock fragments lithology (normalized to andesite + Amalia Tuff) across bench 9, trench LFG-006. Outer oxidized, margin of rock pile is on the left (refer to Figure 9 for geologic section).

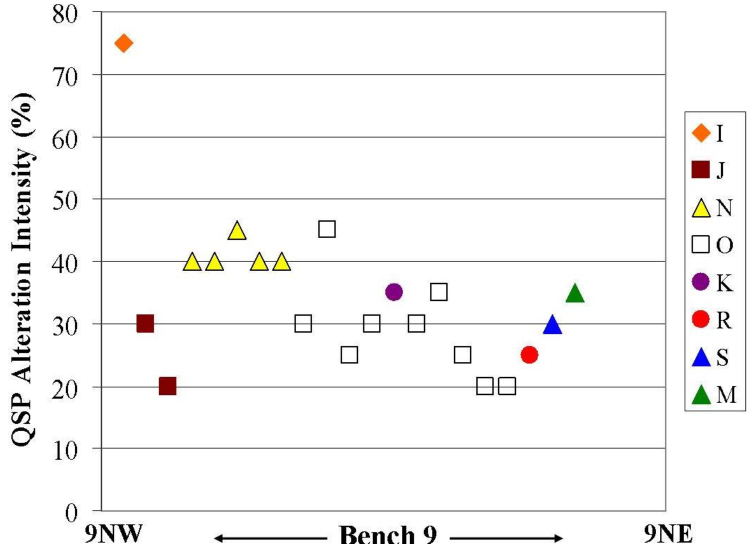

Figure 11. Plot of QSP hydrothermal alteration intensity (defined by the percentage of hydrothermal alteration minerals that have replaced primary minerals) across bench 9, trench LFG-006. Refer to Figure 9 for geologic section.

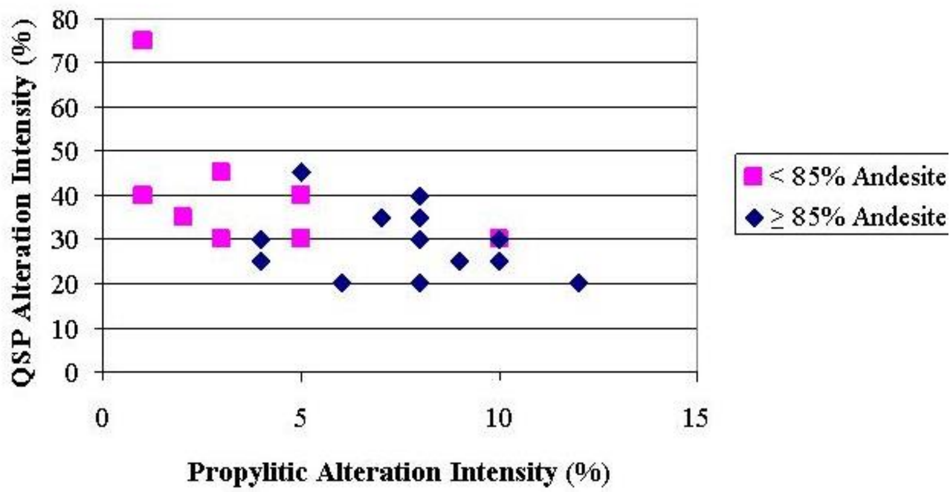

Figure 12. Propylitic hydrothermal alteration intensity versus QSP alteration intensity for rock pile samples from bench 9, trench LFG-006.

Whole rock chemistry obtained for soils from bench 9, trench LFG-006 and normative mineralogy was calculated (CIPW; Best 1982). Calculation of normative minerals provides a semi-quantitative verification of estimates of rock fragment type. The proportion of andesite rock fragments estimated by soil petrography negatively correlated with normative quartz (Fig. 13) and positively correlated with normative plagioclase (Fig. 14). For quartz (Fig. 13), deviation from average Amalia and andesite normative values is attributed to hydrothermal alteration. High degrees of QSP hydrothermal alteration resulted in normative quartz values higher than average Amalia and andesite. Normative plagioclase values for bench 9 samples are lower than average Amalia and andesite (Fig. 14) due to the replacement of primary plagioclase by hydrothermal alteration minerals.

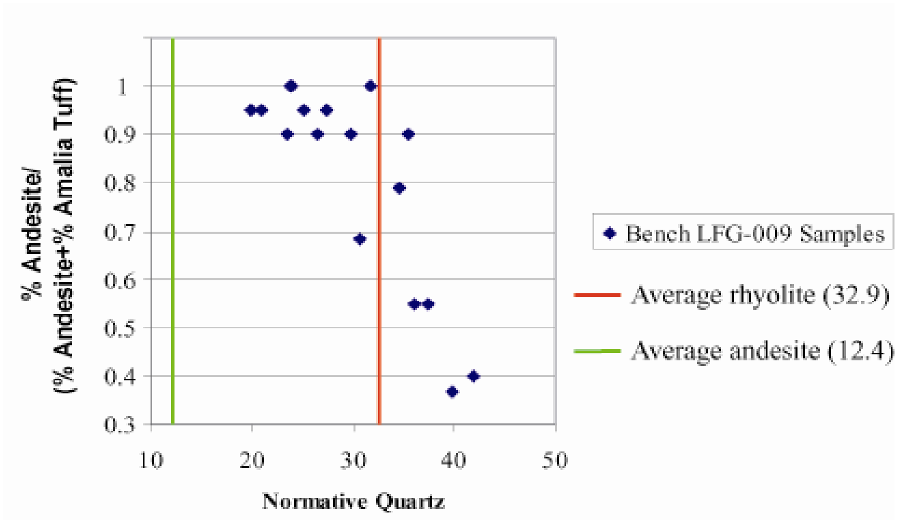

Figure 13. Normative quartz compared with rock fragment type (% andesite, normalized to andesite + Amalia Tuff) for samples from bench 9, trench LFG-006. Normative values for average rhyolite and andesite and shown for reference (Best, 1982).

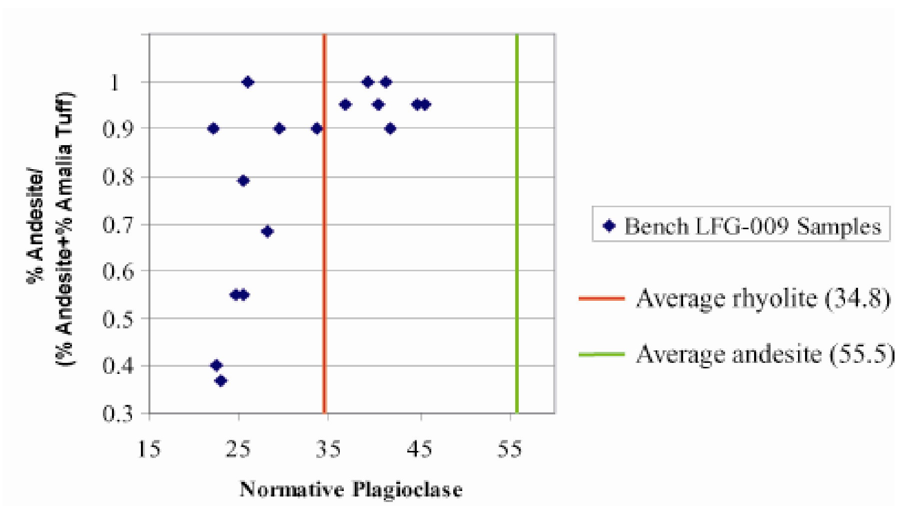

Figure 14. Normative plagioclase versus rock fragment type (% andesite, normalized to % andesite + Amalia Tuff) for samples from bench 9, trench LFG-006. Normative values for average rhyolite and andesite and shown for reference (Best, 1982).

The gypsum-pyrite-carbonate mineral assemblage provided insight into the process of post-mining weathering, which has occurred since the material was emplaced in the rock pile. Gypsum occurred in the piles with distinctly different crystal habits and stable isotope studies have shown that clear, prismatic crystals are authigenic, forming after material was emplaced in the rock pile (Fig. 15; Campbell et al., 2005). This material was likely a product of weathering. Authigenic gypsum abundances decreased from the outer, oxidized margin to the interior portion of the rock pile (Fig. 16). Conversely, carbonate abundance showed a general increase from the outside to the inside of the rock pile (Fig. 17). Additionally, carbonate abundance was correlated to paste pH; samples with abundant carbonate (n=4) have paste pH values between 8.4 and 9.6, whereas those with no detectable carbonate (n=7) have paste pH values between 2.2 and 3.7 (Fig. 18). This finding implies carbonate was at least partially controlling pH by neutralization of produced acid. Pyrite was not common in rock pile samples from bench 9, trench LFG-006. Pyrite comprised up to 2% of unit I, the outermost unit, and otherwise occurred only in trace amounts.

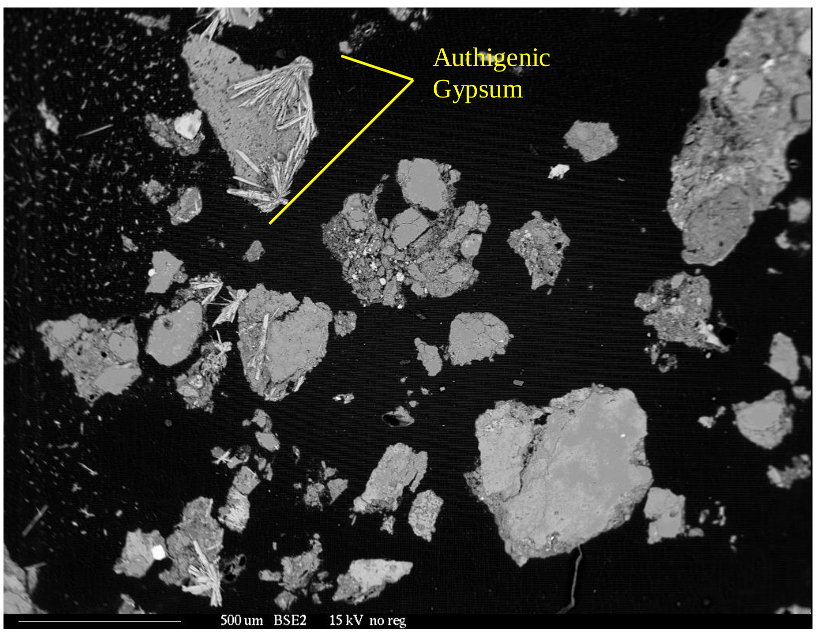

Figure 15. Backscattered electron image of rock pile sample from unit I. Bladed, prismatic crystals are authigenic gypsum.

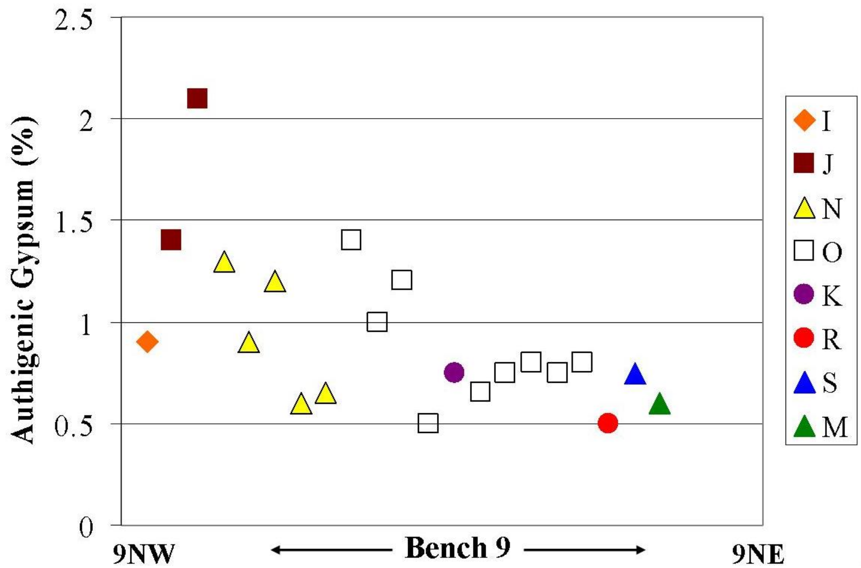

Figure 16. Authigenic gypsum abundance across bench 9, trench LFG-006. Outside of rock pile is on the left (refer to Figure 9 for geologic section).

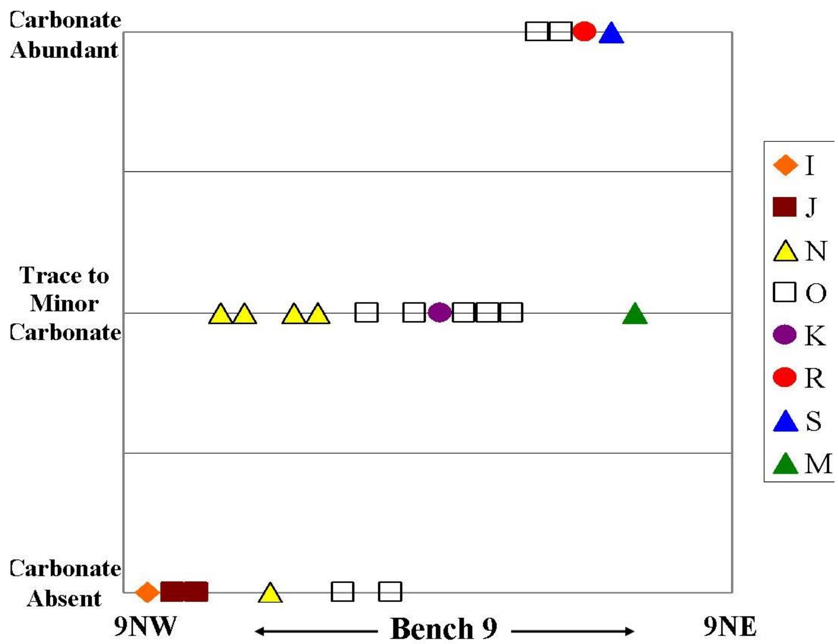

Figure 17. Plot of carbonate abundance across bench 9, trench LFG-006. Refer to Fig. 9 for geologic section.

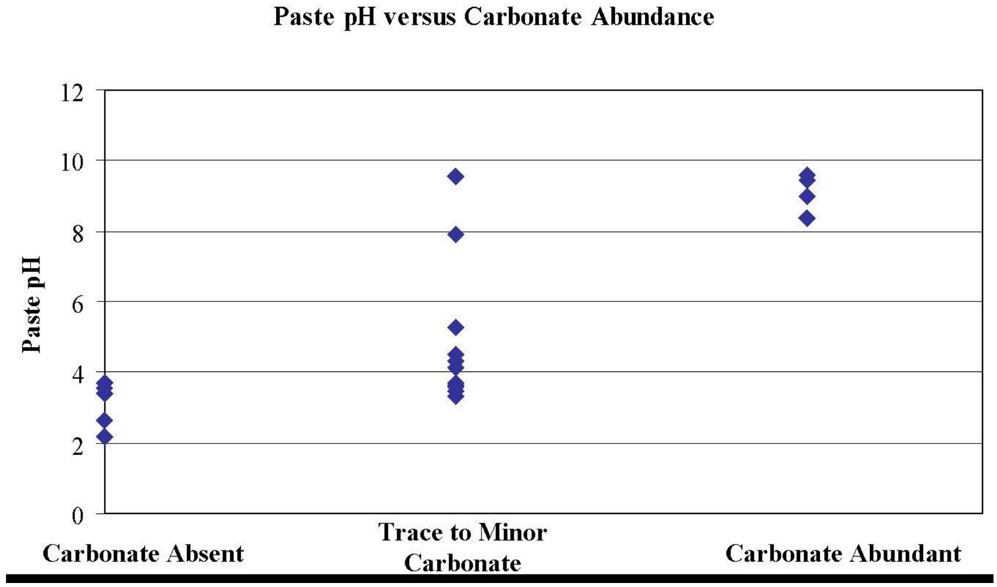

Figure 18. Carbonate abundance versus paste pH for mine rock material from bench 9, trench LFG-006.

Clay mineralogy

Clay mineral analyses of the GHN mine rock pile samples revealed the presence of kaolinite, smectite, illite (mica) and chlorite, as well as, random mixed layer clays. Twenty-one samples along bench 9, trench LFG-006 were analyzed for relative abundances of clay mineral groups (Fig. 19, 20).

Drill core samples from GHN were crushed and analyzed for clay mineralogy to identify the clay mineral groups within the bedrock without the effects of weathering. The results showed that each of the major clay mineral groups found within the rock pile were present within the major lithologies (i.e. rock fragments, Table 5). The QSP hydrothermal altered Amalia Tuff contained predominantly illite and minor amounts of kaolinite. The andesite, both propylitic and QSP hydrothermal altered, contained each of the four main clay mineral groups and random mixed-layer clays. Soil petrographic analyses for lithology and hydrothermal alteration types from bench 9, trench LFG-006 were compared to the relative clay mineral abundances. These results indicated the relative abundances of the clay minerals across bench 9, trench LFG-006 were most likely controlled by the host rock lithology and pre-mining hydrothermal alteration and not post-mining weathering.

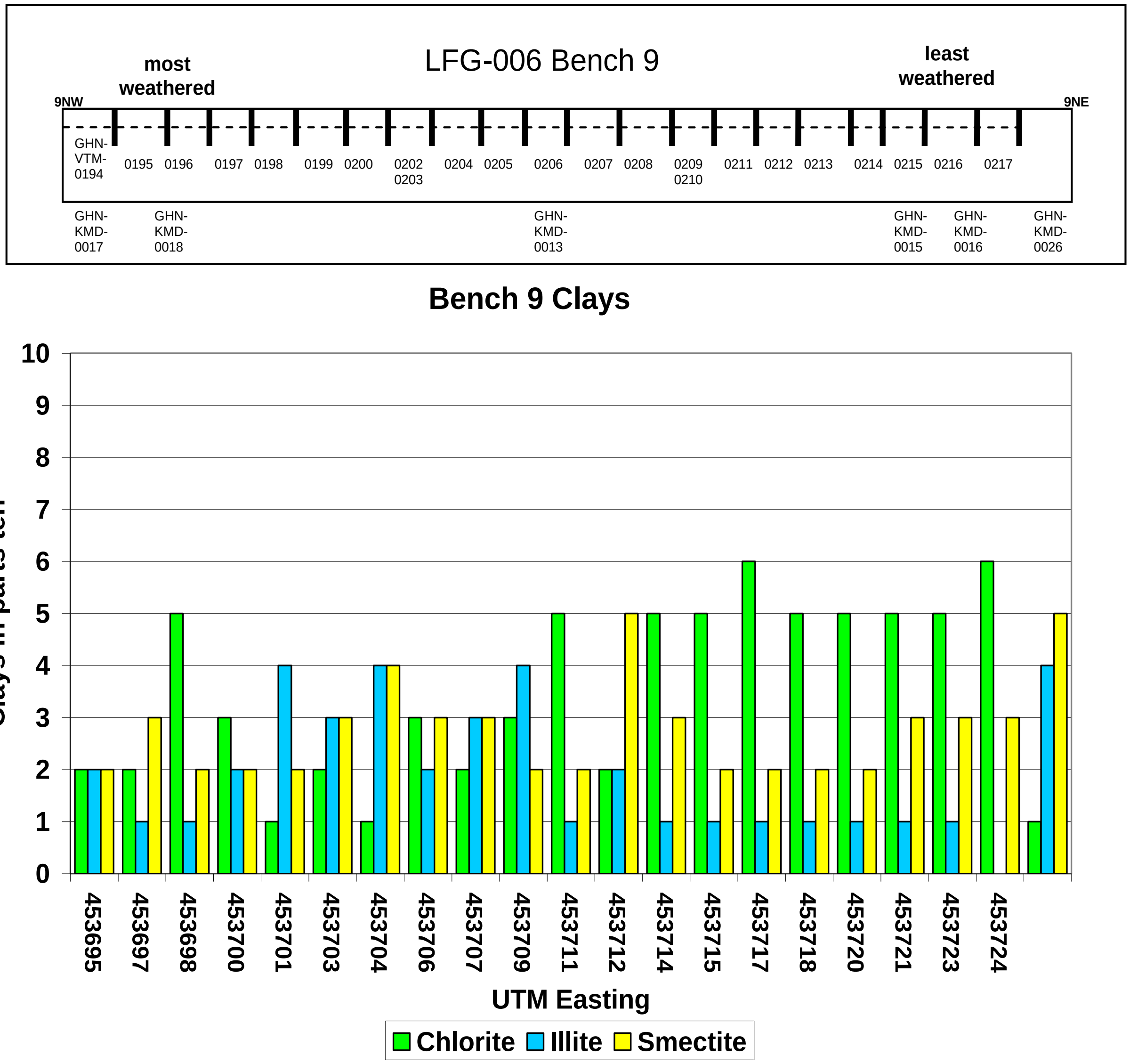

Figure 19. The relative clay abundances of chlorite, illite and smectite for bench 9, trench LFG-006 samples. The major host rock lithologies and hydrothermal alteration type (prop = propylitic, QSP = quartz-sericite-pyrite) were from soil petrographic descriptions of the samples from bench 9. Clay mineral group abundances are reported in parts per ten contained in the total clay mineral fraction (Hall, 2004; Moore and Reynolds, 1989). UTM easting refers to the surveyed location (easting) in meters, NAD 27 CON. Total parts in ten include Fig. 20.

Microprobe analysis of rock fragments within the soil samples indicated the presence of hydrothermal clay minerals replacing the primary igneous phenocrysts and matrix (Fig. 20, 21), which is interpreted to have taken place prior to the rocks being placed in the rock piles (i.e. pre-mining). Geochemical analysis of the hydrothermal clay minerals by microprobe analysis indicated the majority of the clay minerals were chlorite and illite and the chemical compositions were similar to those within the rock pile samples. The physical break-down of the rock during the excavation process and placement into the rock piles most likely released clay minerals contained within the phenocrysts and groundmass and was therefore the source of the clay minerals in the rock piles.

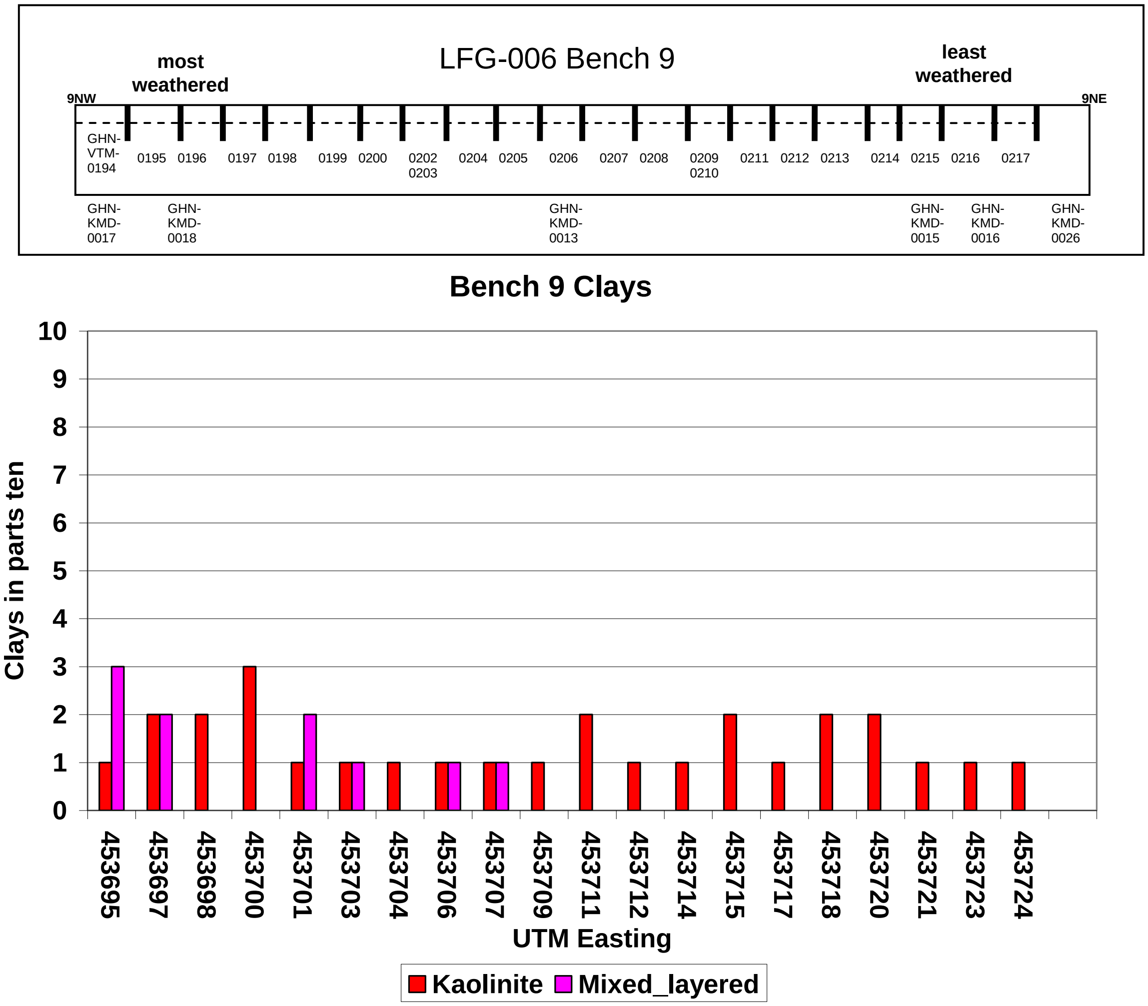

Figure 20. The relative clay abundances of kaolinite and random mixed-layer clays for bench 9, trench LFG-006 samples. The major host rock lithologies and hydrothermal alteration type (prop = propylitic, QSP = quartz-sericite-pyrite) are from soil petrographic descriptions of the samples from bench 9. Clay mineral group abundances are reported in parts per ten contained in the total clay mineral fraction (Hall, 2004; Moore and Reynolds, 1989). UTM easting refers to the surveyed location (easting) in meters, NAD 27 CON. Total parts in ten include Fig. 19.

Table 5. Clay mineral groups of drill core samples within each of the major host lithologies in the GHN rock pile. Colors refer to colors in Figures 19 and 20.

Sample number	**Lithology**	**Hydrothermal alteration**	**kaolinite**	**illite**	**smectite**	**chlorite**	**mixed layer**
PIT-VTM-0006	Amalia Tuff	QSP		yes			
PIT-VTM-0007	Amalia Tuff	QSP		yes	yes		
PIT-VTM-0008	Amalia Tuff	QSP	yes	yes			
GMG-PIT-0001	andesite	propylitic	yes	yes			
PIT-KMD-0007	andesite	QSP		yes			
PIT-KMD-0008	andesite	propylitic		yes		yes	
PIT-VTM-0004	andesite	QSP	yes	yes	yes	yes	yes
PIT-KMD-0009	andesite porphyry	propylitic	yes	yes	yes	yes	yes
GMG-PIT-0009	andesite porphyry	QSP	yes	yes	yes	yes	yes
PIT-VTM-0005	andesite porphyry	QSP		yes			
GMG-PIT-0010	rhyolite breccia	propylitic	yes	yes	yes	yes	yes
GMG-PIT-0011	rhyolite breccia	propylitic	yes	yes			
GMG-PIT-0014	rhyolite porphyry	QSP		yes			
PIT-VTM-0003	rhyolite porphyry	QSP	yes	yes	yes	yes	yes

Figure 20. Feldspar phenocryst replacement of chloritic clay in a rock fragment from the GHN rock pile (sample GHN-KMD-0072-31-06).

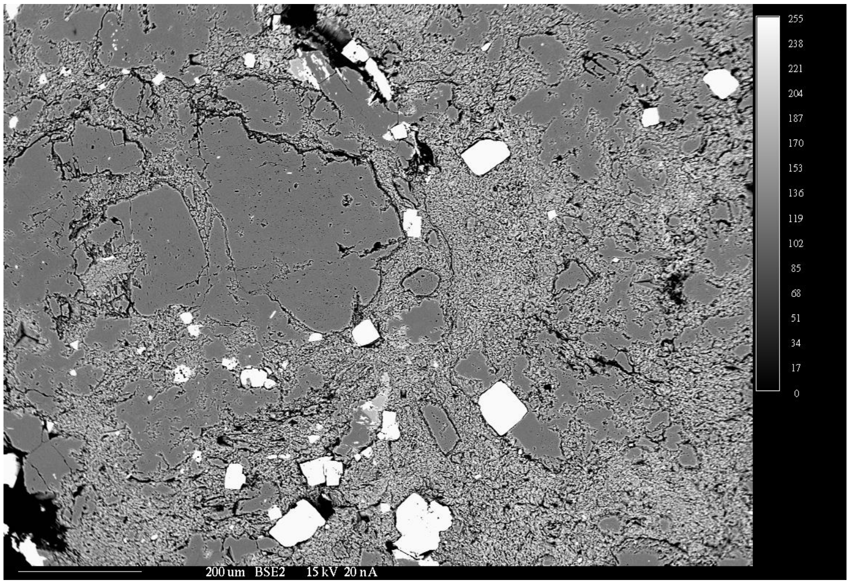

Figure 21. Pervasive clay alteration in rock fragment from GHN rock pile (sample GHN-KMD-0046-31-05).

Summary

Nineteen trenches were constructed in the GHN rock pile as it was regraded in 2004-2005. Detailed geologic mapping and sampling indicated that geologic units could be distinguished and mapped in the rock pile. Units were defined based on grain size, color, texture, stratigraphic position, and other physical properties that could be determined in the field. Units were correlated between benches and to opposite sides of each trench, and several units were correlated downward through the excavated trenches. Eighteen geologic units were differentiated, described, and sampled. Typically, paste pH increased with distance from the outer, oxidized zone (west at GHN) towards the interior units (east at GHN). The outer zone was oxidized (weathered) based upon the white and yellow coloring, low paste pH, presence of jarosite and gypsum, and absence of calcite. However, the oxidation/reduction (weathering) state in the interior zone is not yet determined. The base of the rock pile closest to the bedrock/colluvium surface represents the oldest part of the rock pile since it was laid down first. Portions of the base appeared to be nearly or as oxidized (weathered) as the outer, oxidized zone, suggesting that air and water flow along the basal interface occurred and possibly was an active weathering zone. Characterization of original rock pile material was accomplished by petrographic analysis and included descriptions of rock fragment lithology and alteration type and intensity. Clay mineral analyses revealed the presence of kaolinite, smectite, illite (mica) and chlorite, as well as, random mixed layer clays within the GHN rock pile. Analyses of samples from unweathered, unoxidized drill core samples and from the GHN rock pile are similar in clay mineralogy and composition as determined by XRD and electron microprobe analyses, which suggests that the majority of clay minerals in the GHN samples were derived from the original, pre-mined hydrothermal alteration and not post-mining weathering. The physical break-down of the rock during the excavation process and placement into the rock piles most likely released clay minerals contained within the phenocrysts and groundmass. It is expected that with increased weathering, clay minerals could form in the rock pile in the future.

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