

DRA–27. CHARACTERIZATION OF PHYSICAL AND CHEMICAL WEATHERING IN THE ROCK PILES

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1. STATEMENT OF THE PROBLEM

What are the indications of weathering in the Questa rock piles? What are the physical and chemical weathering processes active at both the surface of and within the rock piles? How do the mineralogy, chemistry, and physical properties of the Questa materials change with weathering? Can the products of these processes be quantified and serve as one or more weathering indices? This DRA summarizes the weathering effects of all of the Questa materials.

2. PREVIOUS WORK

Alteration is a general term describing the changes in mineralogy, texture, and chemistry of a rock as a result of a change in the physical, thermal, and chemical environment in the presence of water, steam, or gas, including those changes produced by weathering (Henley and Ellis, 1983; Reed, 1997; Neuendorf et al., 2005; Ludington et al., 2005). The nature of the alteration depends upon (Browne, 1978; Henley and Ellis, 1983; Ludington et al., 2005):

- Temperature and pressure (including amount of overburden or depth) at the alteration site
- Composition of the parent rock
- Quantity and composition of the altering (invading) fluids
- Permeability of the parent rock
- Duration and intensity of the alteration process (i.e. time)
- Distance from the alteration source, resulting in alteration zoning
- Climate.

Hydrothermal alteration is the change in original composition of rock in situ by hydrothermal (warm to hot) solutions during or after the mineralization. In this study, hydrothermal alteration refers to pre-mining conditions. Alteration includes hypogene and hydrothermal (primary), supergene (secondary), and weathering alteration. *Hypogene alteration* occurred below the surface during the formation of the ore body by upwelling (ascending) hydrothermal or warm to hot fluids (Neuendorf et al., 2005). *Supergene alteration* is the natural weathering, before mining, of the ore body, at low temperatures at and near the Earth's surface by descending fluids (Neuendorf et al., 2005).

Weathering is the set of physical and chemical changes, up to and including disintegration of rock by physical, chemical, and/or biological processes, occurring at or near the earth's surface (e.g. in the vadose zone at temperatures less than or equal to approximately 70°C) that result in reductions of grain size, changes in cohesion or cementation, and changes in mineralogical composition. According to the AGI Geologic Glossary (Neuendorf et al., 2005), weathering is “the destructive process or group of processes by which earthy and rocky materials on exposure to atmospheric agents at or near the earth's surface are changed in color, texture, composition firmness, of form with little or no transport of the loosen or altered material; specifically the physical

disintegration and chemical decomposition of rock that produce an in-situ mantle of waste...” Weathering is simply the consequence of exposing rocks to the conditions at the Earth’s surface as a result of fairly low temperatures, low pressures, organic activity, and chemically active substances such as water and the gases of the atmosphere. There are two general types of weathering that must be examined during this project, physical weathering and chemical weathering. *Physical weathering* involves the physical breakup of a rock by mechanical processes. *Chemical weathering* encompasses changes to the texture structure and composition of the rock fragments due to geochemical and biogeochemical reactions. Physical and chemical weathering processes can overlap in time and space, and it is often difficult to determine which process is most responsible for the observed weathered effects. Many scientists study these processes on a geologic time scale. However, weathering in rock piles, including the Questa weathering stability project, is a study of weathering in engineering time, i.e. tens or hundreds of years, where short-term weathering processes are more important than longer-term processes (Fookes et al., 1988; Geological Society Engineering Group Working Party, 1995).

Diagenesis is a broad term related to the chemical, physical, and biological changes affecting sediment after its initial deposition and during and after its lithification. Diagenesis does not include weathering or metamorphism of the sediment, but does include pedogenesis or the processes that form soils (Neuendorf et al., 2005). In terms of the Questa rock piles (man-made sediment), weathering and diagenetic processes overlap in time and space, especially in cementation of the rock-pile material. Cementation is the diagenetic process where sediments become lithified or consolidated or the binding-together of particles into hard, compacted rocks (Neuendorf et al., 2005). Cementation is important in the Questa study, because cementation could increase the slope stability of the rock piles in both the short (<100 years) and long term (>100 years).

A *weathering index* is a measure of how much the sample has weathered with time (i.e. intensity or degree of weathering). It can best be thought of as reaction progress documenting how far that rock has gone from its initial state toward the end product of weathering. It is not only a function of time, but also of weathering environment. The ultimate objective for the application of the weathering index is to establish relationships between the weathering index (i.e. mineralogy and chemistry) and stability properties for the major rock types present in the rock piles at the Questa mine.

A wide variety of weathering indices have been proposed in the literature (Appendix 1; McLemore et al., 2008c) using physical, geochemical, mineralogical, and geotechnical characteristics. Most of the chemical weathering indices in the literature are based only on geochemical parameters, which restrict their application to the type of environment for which they were developed. These indices typically are based on larger time scales and, in many cases, different climate and geomorphic conditions than those found at Questa.

3. TECHNICAL APPROACH

The technical approach for examining the weathering processes involves an iterative and interactive process addressing both the geotechnical and geochemical characterization of materials. Principal features of the process include the following steps:

1. Compilation and evaluation of existing information on weathering indices and weathering of rock piles from throughout the world (McLemore et al., 2008c, d).
2. Formulation of an initial conceptual geological, geochemical, hydrological, and geotechnical model that can distinguish features of pre-mining hydrothermal alteration and supergene alteration from post-mining weathering in the rock piles (McLemore et al., 2008a, c; McLemore and the Questa Rock Pile Weathering and Stability Team, 2008).
3. Establish and evaluate natural analogs to determine weathering products of similar rocks at a longer time scale (DRA-19, 20, 21; Graf, 2008; McLemore, 2008a, Ayakwah et al., 2008).
4. Geochemical testing
 - a. Examine chemical compositions of water samples collected from seeps, trenches, surface and underground water samples, and runoff waters (McLemore et al., 2008a; Giese et al., 2008; E. Osantowski, in preparation).
 - b. Determine geochemical trends for fresh outcrop samples, using published and new chemical analyses of outcrop, rock pile and drill hole (representing samples from the open pit, i.e. pre-mined overburden) samples (DRA-1; McLemore et al., 2008b).
 - c. Characterize samples from GHN and determine weathering patterns and characteristics (DRA-6; McLemore et al., 2008a).
 - d. Characterize samples from the hot zones on the front rock piles (DRA-7; McLemore et al., 2008g).
 - e. Characterize samples of the rock pile crusts (DRA-8; Giese et al., 2008).
 - f. Characterize weathered and unweathered boulders to understand short-term chemical effects on weathering (DRA-25,; Sweeney et al., 2007).
 - g. Characterize the samples before and after humidity cell testing (DRA-34; McLemore et al., 2008f).
5. Formulation of an initial weathering index (Simple Weathering Index, SWI, Appendix 2; McLemore et al., 2008a).
6. Evaluation of geochemical data and published weathering indices (McLemore et al., 2008c).
7. Formulation of the Questa Mineralogical Weathering Index (QMWI, Appendix 3, DRA-16; McLemore et al., 2008c).
8. Detailed geotechnical testing of a subset of samples for shear strength properties for internal angle of friction and cohesion. Evaluation of geotechnical data (DRA-50; McLemore et al., 2008e).
9. Detailed characterization of in-situ samples and determine relationships between weathering and cohesion (DRA-47).
10. Initial development of integrated models of geotechnical behavior as a function of weathering (DRA-51; McLemore et al., 2008e).
11. After the data sets are initially judged complete, the team will determine whether the provisional weathering index can be tied to the geotechnical data in a manner that would allow development of long-term modeling sufficient for the project requirements.

Mineral abundances were determined by the modified ModAn technique (McLemore et al., 2009; DRA-5), which 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 quantitative mineralogy are in the actual sample analysis using the modified ModAn technique. 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).

4. CONCEPTUAL MODEL(S)

Chemical weathering in almost all literature studies is based upon the acidity derived from the CO₂ system, where the dissolution of feldspar to form clays is the most important chemical reaction (Drever, 1997; Price, 2003). However, in the Questa rock piles, unlike most natural residual soil weathering profiles, dissolution of pyrite, produces H₂SO₄ as the dominant weathering acidic, with subsequent dissolution of calcite, and to a lesser extent chlorite, illite, and other silicate minerals. These reactions result in 1) elevated dissolved solutes in water seeping from the rock piles and 2) the precipitation of gypsum, jarosite, soluble efflorescent salts, and Fe oxide/hydroxide minerals. These reactions can occur within years to hundreds of years, until the source of sulfur is consumed. Weathering or oxidation of pyrite and other sulfide minerals generally requires four components: water, sulfur (sulfide), air (oxygen) and bacteria (Fig. 1; McLemore, 2008b) and the result is sulfuric acid, locally called acid drainage (AD), acid mine drainage (AMD), or acid rock drainage (ARD). The resulting sulfuric acid does not entirely escape the rock pile, but resides as pore fluids, which can dissolve minerals in and at the surface of the rock pile. Water and oxygen appear to be the rate limiting factors in the oxidation of sulfide minerals, especially in arid and semi-arid environments (León et al., 2004). Recent experimental studies by Jerz (2002) and Jerz and Rimstidt (2004) have confirmed earlier work by Morth and Smith (1966) that shows pyrite oxidizes faster in moist air than under saturated conditions, thereby accelerating the weathering of the rock piles, at least locally. Specific factors that affect pyrite oxidation are oxygen concentration, temperature, pH, pyrite surface area, concentration of ferric iron (Fe⁺³), the presence of bacteria or other living organisms, and water.

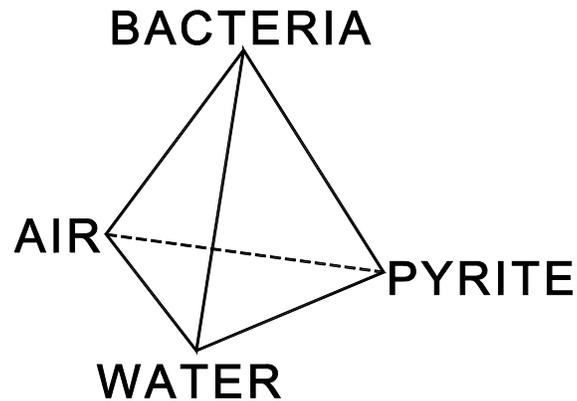


FIGURE 1. Acid drainage (AD) tetrahedron, showing the four components that produce AD (McLemore, 2008b).

The Questa rock piles were formed by blasting of the overburden (material overlying the ore deposit), transported by truck, and dumped by end-haul methods over the edge of the slope into steep valleys near the Questa open pit (URS Corporation, 2003, appendix C). End-haul dumping results in a rock pile that consists of numerous layers that are matrix supported with finer particle sizes at the top of the rock pile and increase in particle size and becomes more cobble supported at the base (DRA-6, McLemore and the Questa Rock Pile Weathering and Stability Team, 2008; McLemore et al., 2008a). The resulting layers locally are at, or near, the angle of repose and subparallel to the original slope angle. Detailed geologic mapping and sampling in the Goathill North (GHN) rock pile at Questa revealed that these layers could be defined as mappable geologic units in the rock pile (Appendix 4, Fig. 4-1; DRA-6; McLemore et al., 2008a). The overburden was fractured before blasting due to pre-mining hydrothermal activity and intrusion of granitic porphyritic and aplitic rocks, resulting in angular rock fragments when blasted (DRA-40; McLemore et al., 2008b).

5. STATUS OF COMPONENT INVESTIGATION

The decrease in grain size that results predominantly from physical weathering results in increased surface area, which leads to greater bulk chemical reactivity and exposure of fresh mineral surfaces. This decrease in grain size can affect the overall particle size distribution, porosity, and permeability, which in part controls fluid flow (both water and gases) in the rock piles. The larger rock fragments are rarely weathered in their interior because of less surface area exposed to weathering. Physical weathering is probably more prominent during end-dumping near time=0 than in the future since it is more predominant at the surface of the rock piles. Common physical weathering processes that are relevant to the Questa rock piles include:

- Freeze/thaw and related frost-action effects
- Thermal expansion and contraction of rock
- Deformation (up to crushing) of rock fragments due to the weight of overlying rock

- Pressure release (also known as stress release weathering) on rock by erosion or other removal of overlying materials
- Growth of plants and living organisms (including micro-organisms) in rock
- Volume change due to mineral reactions (e.g., the hydration of anhydrite to gypsum)
- Abrasion
- Crystallization (i.e. halite crystallization increases volume up to 5%)
- Wetting/drying cycles.

A special case that is relevant to Questa rock piles is the physical breakup of the rock by the volume change resulting from transformation of anhydrite to gypsum or other crystal growth along fractures (DRA-17; Sweeney et al., 2007; Campbell and Lueth, 2008). Crystallization of mineral phases also can break up the rock, for example the crystallization of halite increases the volume by as much as 5%. Examination of weathered/unweathered boulders indicates that disintegration is in part related to physical and chemical weathering along veins, fractures, and pyrite and calcite sites (DRA-25; Sweeney et al., 2007). These physical weathering processes cannot be quantified except perhaps by slake durability and point load indices, which also are a measure of chemical alteration (Viterbo, 2007; Ayakwah et al., 2009; DRA-46). Boulders on the surface of the rock pile break also down through freeze-thaw and chemical weathering processes (DRA-25).

The particle shape and size distributions in the older analogs and the rock piles are similar and suggest that weathering has not affected the shape of the rock fragments (Nunoo et al., 2009). Smaller particles retain angularity after breakdown of larger size particles in the rock piles and analogs (DRA-40). There is no evidence for selective release and migration after deposition in the rock piles of clay-sized or clay-mineral fines to produce continuous zones of clay minerals. There are lenses of clay material with finite lateral extensions (less than 1 m) that were observed near the surface of rock piles and were due to deposition of hydrothermal clays during mining.

Samples of rock fragments from the Questa rock piles and analog materials have high durability and strength even after having undergone hydrothermal alteration and blasting prior to deposition and after potential exposure to weathering for 25-40 years (DRA-46; Viterbo, 2007). The slake durability indices from GHN are high to extremely high according to the slake durability index classification, and the point load indices are medium to very high according to the point load strength index classification (DRA-46). Samples from the GHN rock pile are similar in slake durability and point load indices regardless of geologic layer and location within the rock pile, except that some, but not all samples located in the outer, weathered edge of the rock pile (units C and I) are weaker and have lower slake durability and point load indices. The slake durability indices from the analog sites (alteration scars, debris flow, weathered bedrock, colluvium) are similar to those for the Questa rock piles, i.e. high to extremely high according to the slake durability index classification and the point load indices are medium to very high according to the point load strength index classification (DRA-46). Collectively, these results suggest that future weathering (<1000 years) will not substantially decrease the strength indices of the rock piles with time.

It is difficult, but possible to distinguish between pre-mining hydrothermal alteration and post-mining weathering by using detailed field observations and

petrographic analysis that includes defining the paragenesis (sequence of events), especially using microprobe analyses (McLemore et al. 2008a, c), because of both the fine-grained texture of the soil-like matrix material and the extensive pre-mining hydrothermal alteration. Some of the rock in the rock piles also had been weathered in the natural supergene environment before open-pit mining began (Campbell and Lueth, 2008). The field observations and petrographic analyses are important to understand in order to properly evaluate the mineralogy and chemistry of the rock piles. The evidence for weathering in the Questa rock piles includes (McLemore et al., 2008a, c):

- 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 (Appendix 4, Fig. 4-2). However, the mineralogical effect of the fast-reacting (less than 40 yrs) weathering pyrite system is to produce precipitates of secondary reaction minerals on the surface of existing rock fragments and within the soil matrix, which result in the yellow to orange color, reflecting the role of ferric iron in the mineral structures. The secondary precipitates form coatings on exterior surfaces, rims, and fill macro- and micro-fractures. Thus, the macro-scale impression of weathering, caused by the discoloration from the observed secondary precipitates is exaggerated.
- Thin yellow to orange, “burnt” layers within the interior of GHN, where water and/or air flowed and oxidized the rock-pile material.
- Paste pH, in general, is low in oxidized, weathered samples and paste pH is higher in less weathered samples (Appendix 4, Fig. 4-3).
- Increase in abundance of jarosite, gypsum, Fe oxide minerals and soluble efflorescent salts (locally as cementing minerals), and low abundance to absence of calcite, pyrite, and epidote in weathered samples (Appendix 4, Fig. 4-4).
- Textures of gypsum crystals indicate in-situ formation with supporting evidence from sulfur and oxygen isotopes (Campbell and Lueth, 2008).
- Tarnish or coatings of pyrite surfaces, as well as more complete oxidation or dissolution of pyrite within weathered samples (Appendix 4, Fig. 4-5; Heizler et al., 2007).
- 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 (Appendix 4, Fig. 4-6; McLemore et al., 2008a, c).
- Change in bulk texture of the rock-pile material as compared to the original mined material, including increase in soil:rock ratio, piping or stoping within the rock pile, and decrease in grain size due to physical weathering (Appendix 4, Fig. 4-7)
- Chemical classification as potential acid-forming materials using acid base accounting methods (Appendix 4, Fig. 4-8; Tachie-Menson, 2006).
- The chemical composition of waters from the Questa rock piles (i.e., seeps and runoff waters from the rock piles, chemistry of leachate waters obtained by laboratory leaching of rock pile samples) imply that silicate dissolution is occurring within the rock piles in a similar manner as that suggested by surface and ground water documented in the alteration scars by Nordstrom et al. (2005).
- The chemical analyses of these water samples are characterized by acidic, high sulfate, high TDS (total dissolved solids), and high metal concentrations. Sulfate

is the predominant anion and Al, Mg, Fe, and Mn are the predominant cations. The chemical analyses of these waters reflect the dissolution of calcite, pyrite, gypsum, and soluble sulfate and hydroxide minerals. The high Mg and Al in the waters possibly are related to chlorite, epidote, and other clay minerals are likely a result of incongruent dissolution (i.e. selective removal of cations) by the acidic waters. This is supported by the acidic leaching of clay minerals experiments in the laboratory (Donahue, 2008). The high Mn is possibly related to Mn-bearing carbonate (calcite, dolomite, rhodochrosite), chlorite, epidote, and smectite. The high F is possibly related to dissolution of fluorite, illite, beryl, apatite, and smectite, which contain anomalous fluorine concentrations (McLemore et al., 2008b). The high Fe and S are possibly related to the dissolution of pyrite and other sulfide minerals.

Not all weathered samples exhibit all of these features. It is common to have the fine-grained soil matrix be weathered, but most rock fragments within the rock-pile material exhibit little or no weathering (DRA-2). A rock containing stockwork veins with pyrite and calcite can weather under oxidizing conditions as the pyrite oxidizes, calcite dissolves, and secondary gypsum and iron oxides precipitate; the mineralogical changes can be observed microscopically and, locally, macroscopically. Extensive evidence of mineral transformations due specifically to weathering in the rock pile is not observed (i.e. feldspar to kaolinite).

Strong mineralogical evidence for very recent growth of minerals is most persuasive in the surface crusts that form on the surface of the rock pile (DRA-8). Both the rock textures and the detailed mineralogical observations (by optical microscopy, X-ray diffraction, spectral analysis, and scanning electron microscopy) show that evaporite minerals, largely gypsum and jarosite, but including various hydroxysulfates or efflorescent salts, cemented aggregates of silt and fine sand. The fine-grained detrital material appears to be due to the mechanical breakdown of larger rock fragments at and very near the surface of the rock piles, probably largely through original blasting during mining, subsequent mineral precipitation along fractures, and subsequent freeze-thaw cycling (Borden, 2001). The gypsum forms from pore water, high in sulfate (from near-surface pyrite oxidation) and calcium (from dissolution of calcite and other Ca-bearing minerals) in response to the acidification of pore water. The pore water evaporates (DRA-32), and the gypsum and evaporative salts form in this process as the degree of evaporation increases and the evolving solutions reach thermodynamic saturation with the evaporite minerals. Because the process is happening close to the surface of the pile where oxygen is abundant, iron oxides and hydroxysulfates also precipitate.

The original QRPWASP hypothesis was that if there are systematic processes that represent weathering and if those processes are time dependent, then it is reasonable to expect that there would be progressive changes in rocks and minerals related to the intensity and duration of weathering. If these processes and rates could be understood for the systems observed at Questa, there would be a rational basis for projecting current conditions forward in time. If a set of samples could be obtained that spanned a range of weathering (that is, across a “weathering index”), then those samples could be tested for key geotechnical parameters related in known ways to shear strength. This would then give an empirical relationship between extents of weathering and shear strength. If that

extent of weathering could be extrapolated forward in time, one would have a tool suitable for projecting shear-strength behavior into the future.

Numerous weathering indices were evaluated (Appendix 1) for their applicability in the Questa rock piles (McLemore et al., 2008c). A simple weathering index (SWI) was developed to differentiate the visual weathering intensity of Questa rock-pile materials (Appendix 4; McLemore et al., 2008a). Five classes (Table 2-1) describes the SWI classification for the mine soils at the Questa mine based on relative intensity of both physical and chemical weathering (SWI=1, least weathered to SWI=5, most weathered; modified in part from Little, 1969; Gupta and Rao, 1998; Blowes and Jambor, 1990). The determination of relative intensity is based on the surface character of the larger rock fragments and the soil matrix; however, the interior of the rock fragments can be unweathered even though the surface and surrounding matrix is weathered. The Questa Mineralogical Weathering Index (QMWI) was developed as a measure of the short-term mineralogical changes within the rock-pile material, specifically the pyrite-calcite-gypsum-jarosite system (DRA-16, Appendix 6; Table 4-1; McLemore et al., 2008c). Other indices or parameters that can be used to indicate some aspects of weathering in the Questa rock piles include paste pH, authigenic gypsum, sum of gypsum and jarosite, SO_4 , slake durability index, point load index and Net NP (neutralizing potential; Appendix 4, Fig. 4-8; McLemore et al., 2008c).

6. RELIABILITY ANALYSIS

Samples collected for the project are complete, comparable, and representative of the defined population at the defined scale. Precision and accuracy are measured differently for each field and laboratory analysis (parameter), and is explained in the project reports, SOPs and summarized in DRA-0 and McLemore and Frey (2008). 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 the various technical studies documented in the individual component DRAs and ultimately supports the programmatic DRA.

Some of the technical and data uncertainties in this DRA include:

- The mineralogical and petrographic techniques used for this study are not able to detect small differences in the types of clay minerals or minor changes in their mineral chemistry.
- Only the upper third of the stable portion GHN rock pile was trenched, mapped, and sampled, although three drill holes also were drilled into the rock pile; these data were extrapolated for the entire rock pile. Samples from the surface of the toe of GHN were used to define the toe region.
- 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, except by detailed field

observations and petrographic analysis and the changes due to hydrothermal alteration are more pronounced than those due to weathering.

7. CONCLUSIONS OF THE COMPONENT

In the Questa rock-pile and analog materials, dissolution of pyrite, calcite, and to a lesser extent some combination of chlorite, illite, feldspars, smectite, and other silicate minerals are the predominant chemical reactions that results in 1) elevated dissolved solute concentrations in water seeping from the rock pile and analog sites and 2) the precipitation of gypsum, jarosite, soluble efflorescent salts, and Fe oxide/hydroxide minerals. Oxygen and water are available at and near the surface of the rock piles, at and near the base of the rock pile, in local permeable strata within the rock pile, and along cracks and crevasses cutting across the strata. See DRA-1, 3, 4, 6, 7, 7a, 8, 19, 20, 21, 22, and 34 for more details. All of the detailed studies (i.e. hot zones, DRA-7; boulder studies, DRA-25; GHN, DRA-6; Questa rock piles, DRA-2; and weathering cells, DRA-34) indicate that the pyrite-calcite-gypsum weathering system is the predominant weathering system in the Questa materials and that the slower silicate dissolution is minor in the record of the current rock piles.

Weathering generally decreased from the outer edge of the GHN rock pile to its interior and then increased toward the base of the rock pile where water and oxygen are available to dissolve pyrite and calcite to form gypsum, jarosite, soluble efflorescent salts and Fe oxide/hydroxide minerals. Weathering also is found in specific layers within the interior of the Questa rock piles where water and air are available (DRA-6; McLemore et al., 2008a).

Cohesion at the formation of the rock piles was zero, so any cementation documented in the rock piles is the result of weathering or diagenesis. Authigenic gypsum, jarosite, soluble efflorescent salts, Fe oxide minerals and to a lesser extent, clay minerals (liberated from the mined rock material during construction of the rock piles, i.e. pre-mining clay minerals), have cemented parts of the Questa rock-pile material (DRA-3, 6, 8, 25, 27a, 34; Appendix 4, Figs. 4-9, 4-10; McLemore et al., 2008a).

The majority, if not all of the clay minerals were not formed as the result of chemical precipitation in the rock pile under low pH during weathering over the last 25-40 years, but were formed by hydrothermal alteration of the rocks before mining. There are eight principal lines of evidence that the clays in GHN are predominantly from the hydrothermal alteration of the host lithologies prior to excavation and emplacement in to the GHN rock pile and not formed by weathering (Donahue et al., 2007, 2009):

- Electron microprobe back-scatter (BSE) images of the drill-core samples through the original host rock before mining shows evidence of primary igneous minerals being replaced by pre-mining, hydrothermal clay minerals (DRA 3; Appendix 4, Fig. 4-11a). The contacts between the sand-size rock fragments and mineral grains within the fine-grained soil matrix are sharp and do not indicate the in-situ formation of the clay minerals into the fine-grained soil matrix (DRA 3, Appendix 4, Fig. 4-11b, c). There is no petrographic, mineralogic, or isotopic evidence for formation of new clay minerals by chemical weathering in either the rock piles or in the natural analog materials.
- Presence of fresh or lightly tarnished pyrite surrounded by clay minerals (Appendix 4, Fig. 4-12; Heizler et al., 2007; McLemore et al., 2008a).

- The GHN clay minerals from the fine-grained soil matrix and rock fragments have similar clay mineral chemical compositions.
- The unweathered drill core and samples from GHN have similar types and abundances of clay mineral groups based on XRD analyses. Chemical analyses of clay minerals from electron microprobe analysis reveal similar chemical compositions for the clays from the two environments (unweathered drill core versus weathered GHN rock pile material; Appendix 4, Fig. 4-13).
- Stable isotope analyses of hydrogen and oxygen of clay mineral separates from rocks throughout the area show that, to the limit of analytical detection, all clay minerals are hydrothermal in origin, with minimum temperatures of formation $>100^{\circ}\text{C}$ (Fig. 6; DRA-17; Graf, 2008; Donahue et al., 2009; Appendix 4, Fig. 4-14).
- Modeled mineral stabilities show that clay minerals are not stable in the acidic environment of pyrite oxidation documented by the Goathill North seep chemistry (DRA-30).
- Pre-mining hydrothermal clays will dissolve incongruently in a sulfuric acid environment as determined from acid leaching experiments on Questa clay minerals (Donahue, 2008).
- Persistence of $2M_1$ illite and pyrophyllite in the alteration scars and fine-grained soil matrix of rock-pile materials indicates the hydrothermal clay minerals predominate in the fine-grained soil matrix (Donahue et al., 2009).

In the last month of the Project, an analysis that employed an innovative and previously undescribed technique reported evidence for tritium in structural hydroxyls (Marston, 2009). The new data showed modern tritium in size fraction $<150\ \mu\text{m}$ from samples that are believed to contain clay minerals. Although the mineralogy of the tested samples is not yet known and no mechanism for hydrogen exchange to structural positions at low temperature has been suggested, the new tritium data are consistent with a modification of clay-minerals by interaction with recent (<20 years) water. If this is confirmed, it suggests that the deuterium in clay minerals also may have exchanged. This new tritium data are not inconsistent with a hydrothermal origin for the clay minerals.

A wide variety of weathering indices have been proposed in the literature (Appendix 1; McLemore et al., 2008c, annotated bibliography) using physical, geochemical, mineralogical, and geotechnical characteristics. However, changes of mineralogy and chemistry between the outer, oxidized zone and the interior, unoxidized zones of the Questa rock piles are a result of differences due to pre-mining composition as well as chemical weathering. These differences can be difficult to distinguish, except by detailed field observations and petrographic analysis (especially electron microprobe analysis) and the variations due to hydrothermal alteration are more pronounced than those due to weathering. Weathering processes, intensity, and rates will differ throughout the rock piles. Because weathering intensities and effects are so variable and dependent upon many factors, no single weathering index is valid over the entire spectrum of weathered states (Aydin and Duzgoren-Aydin, 2002). Furthermore, the variations due to hydrothermal alteration are greater than the variations due to weathering in the Questa materials. Therefore, geochemical signatures of weathering should be used to define weathering before the indiscriminate use of weathering indices (Duzgoren-Aydin, et al., 2002). However, several indices can be used to indicate some aspects of weathering in

the Questa rock piles: SWI (Simple Weathering Index, Appendix 4, Fig. 4-15), QMWI (Questa Mineral Weathering Index, Appendix 4, Fig. 4-15), paste pH (Appendix 4, Fig. 4-3), amount of authigenic gypsum (Appendix 4, Fig. 4-8), sum of the amounts of gypsum and jarosite (Appendix 4, Fig. 4-8), SO_4 (Appendix 4, Fig. 4-8), slake durability index (Appendix 4, Fig. 4-16), point load index (Appendix 4, Fig. 4-17) and Net NP (neutralizing potential; Appendix 4, Fig. 4-8). Collectively these indices, field observations and textural data from petrographic and electron microprobe studies suggest that weathering in many portions of the Questa rock piles is minor to insignificant, except in the outer layers of GHN and in specific layers where water or water vapor moves and oxidizes available pyrite.

Even though some weathering indices were developed that show some aspect of the weathering at Questa, a weathering index that could be related to the geotechnical parameters and be used to predict the future effect of weathering on geotechnical parameters with time could not be developed, because:

- The weathering indices cannot adequately differentiate between the hydrothermal alteration present in the original rock and subsequent alteration due to weathering
- Geotechnical parameters are not controlled by lithology or mineralogy (DRA-42, 47, 50).
- The existence of surface coatings provides little evidence of the extent of weathering of the interior of the rock fragments and the rock fragments comprise most of the rock-pile sample.
- The chemical weathering indices, adapted from literature citations (McLemore et al., 2008d) mostly are based largely on hydrolysis of silicates, which is minor at Questa.
- The “Simple Weathering Index” (SWI), which was used as a field-screening tool, is based largely on the visual characteristics of the soil matrix, particularly color, presence or absence of igneous textures, cementation, and presence or absence of pyrite, calcite, jarosite, and gypsum. Color is exaggerated because it is related to coatings of the rock fragments.
- The site-specific Questa Mineralogic Weathering Index (QMWI, DRA-16) includes the faster weathering system of pyrite, calcite and gypsum, but also has the potential to reflect systematic changes in the bulk rock-fragment materials and because of the very small mass changes that have occurred in 25-40 years the ability to distinguish weathering mineralogically in the manner of QMWI did not have sufficient power to establish reliable trends.
- In the low pH system as in the Questa rock piles, the dominance of congruent weathering reactions and the similarity of dissolution rates for many aluminosilicates results in only subtle changes since most minerals would simply dissolve from the exterior inward without leaving a pseudomorphous successor.
- The QRPWASP mineralogical and geochemical data show that the extent of silicate weathering in the rock piles is slight and that there is not enough variation in solid phase chemistry to lie outside the range of mineral chemistries present in the starting materials due to their protolithologic variation and, especially, the additional redistribution of mass associated with the extensive hydrothermal alteration.

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9. TECHNICAL APPENDICES

- McLemore, V.T., Donahue, K., Dunbar, N. and Heizler, L., 2008d, Characterization of physical and chemical weathering in the rock piles and evaluation of weathering indices for the Questa rock piles: unpublished report to Chevron, Task 1.3, B1.1.

APPENDIX 1. WEATHERING INDICES

Summary of weathering indices (modified from Ng et al., 2001; Duzgoren-Aydin et al., 2002; Price and Velbel, 2003; McLemore et al., 2008c).

Symbol	Weathering index	Optimum fresh value	Optimum weathered/ altered value	Ideal trend (increased weathering/ alteration)	Allows Al mobility	Reference
R (Ruxton Ratio) (assumes mobile/ immobile)	$\text{SiO}_2/\text{Al}_2\text{O}_3$	>10	0	decrease	No	Ruxton (1968), Chittleborough (1991), Arel and Tuğrul (2001), Irfan (1996, 1999)
WIP (Weathering Index of Parker)	$100 [(2\text{Na}_2\text{O}/0.35) + (\text{MgO}/0.9) + (2\text{K}_2\text{O}/0.25) + (\text{CaO}/0.7)]$	>100	0	decrease	Yes	Parker (1970), Arel and Tuğrul (2001)
V (Vogt's Residual Index)	$(\text{Al}_2\text{O}_3 + \text{K}_2\text{O})/(\text{MgO} + \text{CaO} + \text{Na}_2\text{O})$	<1	Infinite	increase	No	Vogt (1927), Roaldset (1972), Arel and Tuğrul (2001)
CIA (Chemical Index of Alteration)	$100 [\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})]$	< 50	100	increase	No	Nesbitt and Young (1982), Arel and Tuğrul (2001)
CIW (Chemical Index of Weathering)	$100 [\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O})]$	< 50	100	increase	No	Harnois and Moore (1988), Maynard (1992), Arel and Tuğrul (2001)
PIA (Plagioclase Index of Alteration)	$100 [\text{Al}_2\text{O}_3 - \text{K}_2\text{O}/(\text{Al}_2\text{O}_3 + \text{CaO} + \text{CaO} + \text{Na}_2\text{O} - \text{K}_2\text{O})]$	< 50	100	increase	No	Fedo et al. (1995)
STI (Silica-Titania Index)	$100 [(\text{SiO}_2/\text{TiO}_2)/((\text{SiO}_2/\text{TiO}_2) + (\text{SiO}_2/\text{Al}_2\text{O}_3) + (\text{Al}_2\text{O}_3/\text{TiO}_2))]$	>90	0	decrease	No	Jayawardena and Izawa (1994)
Alumina-titania Index	$100[(\text{Al}_2\text{O}_3/\text{TiO}_2)/((\text{SiO}_2/\text{TiO}_2) + (\text{SiO}_2/\text{Al}_2\text{O}_3) + (\text{Al}_2\text{O}_3/\text{TiO}_2))]$			increase	no	Jayawardena and Izawa (1994)
Fe/Na	Fe/Na			increase	n/a	Garrett and Lalor (2005)
WPI (Weathering Potential Index)	$100*(\text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO} + \text{MgO} - \text{H}_2\text{O})/(\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 + \text{FeO} + \text{TiO}_2 + \text{CaO} + \text{MgO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$	>20	1100	decrease		Reiche (1943), Irfan (1996, 1999)
PI (Product Index)	$100*\text{SiO}_2/(\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 + \text{FeO} + \text{TiO}_2)$	>80	60	decrease		Reiche (1943), Arel and Tuğrul (2001)
Mg index	$100*(\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3 + \text{MgO}))$			decrease	no	Maynard (1992)
MI (Miura Index)	$(\text{MnO} + \text{FeO} + \text{CaO} + \text{MgO} + \text{Na}_2\text{O} + \text{K}_2\text{O})/(\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3 + 3*\text{H}_2\text{O})$					Miura (1973), Hodder (1984)
MWPI	$100*(\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO} + \text{MgO})/(\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO} + \text{MgO} + \text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 + \text{T})$			decrease		Vogel (1975), Arel and Tuğrul (2001)
SOC (Sesquioxide)	$\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$					Irfan (1996)

Symbol	Weathering index	Optimum fresh value	Optimum weathered/ altered value	Ideal trend (increased weathering/ alteration)	Allows Al mobility	Reference
content)						
Lc (Leaching coefficient)	$\text{SiO}_2/(\text{K}_2\text{O}+\text{Na}_2\text{O}+\text{CaO}+\text{MgO})$				n/a	Li et al (1995)
Rc (Residual coefficient)	$(\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3)/(\text{K}_2\text{O}+\text{Na}_2\text{O}+\text{CaO}+\text{MgO})$					Li et al (1995)
Kr (Silica-Sequioxide Ratio)	$\text{SiO}_2/(\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3)$				no	Moignien (1966)
Hydration Coefficient	$\text{H}_2\text{O}/(\text{K}_2\text{O}+\text{Na}_2\text{O}+\text{CaO}+\text{MgO})$				n/a	Li et al (1995)
ACN Alumina to Calcium-sodium oxide ratio (Harnois)	$\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3+\text{CaO}+\text{MgO})$					Harnois and Moore (1988)
AKN Alumina to potassium-sodium oxide ratio	$\text{Al}_2\text{O}_3/(\text{K}_2\text{O}+\text{Na}_2\text{O})$					Harnois and Moore (1988)
Petrographical weathering index Ipw	WP/(1-WP) WP is percent weathered minerals				n/a	Tuğrul and Gurpinar (1997), Bell and Jermy (2000)
Rm secondary mineral rating	$(\sum(P*M))*T$ P is percent secondary minerals, M mineral rating, T textural rating				n/a	Cole and Sandy (1980), Bell and Jermy (2000)
Brown	$\text{Ln}(\text{K}/\text{Hf})$				n/a	Brown et al. (2003)
Brown	$\text{Ln}\left\{\frac{\text{Fe}/\text{Sc}}{(\text{FeO}/\text{ScO})}\right\}$				n/a	Brown et al. (2003)
Brown	$\text{Ln}(\text{Fe}/\text{As})$				n/a	Brown et al. (2003)
Brown	$\ln(\text{Al}_2\text{O}_3/\text{g}(\text{ACNK}))$				Yes	Von Eynatten et al. (2003)
Brown	$\ln((\text{CaO}^*+\text{Na}_2\text{O})/\text{Al}_2\text{O}_3)$				No	Von Eynatten et al. (2003)
Brown	$\ln(\text{Na}_2\text{O}/\text{Al}_2\text{O}_3)$				no	Von Eynatten et al. (2003)
Al	$(\text{K}_2\text{O}+\text{Na}_2\text{O})/(\text{K}_2\text{O}+\text{MgO}+\text{Na}_2\text{O}+\text{CaO})$				n/a	Piché and Jébrak (2004)
Al2	$100(\text{K}_2\text{O}+\text{MgO})/(\text{K}_2\text{O}+\text{MgO}+\text{Na}_2\text{O}+\text{CaO})$				n/a	Ishikawa et al. (1976), Large et al. (2001)
CCPI	$100(\text{MgO}+\text{FeO})/(\text{MgO}+\text{FeO}+\text{Na}_2\text{O}+\text{K}_2\text{O})$				n/a	Large et al. (2001)
Bases to Alumina	$(\text{K}_2\text{O}+\text{Na}_2\text{O}+\text{CaO}+\text{MgO})/\text{Al}_2\text{O}_3$				Yes	Colman (1982)
Ba (Bases to Alumina)	$(\text{K}_2\text{O}+\text{Na}_2\text{O}+\text{CaO})/\text{Al}_2\text{O}_3$				yes	Rocha Filho et al (1985), Duzgoren-Aydin et al., 2002)
ba1 K-Na to Al	$(\text{K}_2\text{O}+\text{Na}_2\text{O})/\text{Al}_2\text{O}_3$				no	Rocha Filho et al (1985), Duzgoren-Aydin et al., 2002)
ba2	$(\text{CaO}+\text{MgO})/\text{Al}_2\text{O}_3$				no	Rocha Filho et al (1985), Duzgoren-Aydin et al., 2002)

Symbol	Weathering index	Optimum fresh value	Optimum weathered/ altered value	Ideal trend (increased weathering/ alteration)	Allows Al mobility	Reference
ba3	$(K_2O+Na_2O+MgO)/Al_2O_3$				no	Rocha Filho et al (1985), Duzgoren-Aydin et al., 2002)
Colman	$(K_2O+Na_2O+CaO+MgO)/(Al_2O_3+Fe_2O_3+TiO_2)$				Yes	Colman (1982)
Alkali ratio	$100*K_2O/(K_2O+Na_2O)$				n/a	Sueoka (1988)
Birkeland	$SiO_2/(Al_2O_3+Fe_2O_3+TiO_2)$				No	Birkeland (1999)
Chittleborough	$(CaO+MgO+Na_2O)/TiO_2$				n/a	Chittleborough (1991)
WR	$(CaO+MgO+Na_2O)/ZrO_2$				n/a	Chittleborough (1991)
WI-1	$(SiO_2+CaO)/(Fe_2O_3+TiO_2)$				n/a	Darmody et al. (2005)
WI-2	$(SiO_2+CaO)/(Al_2O_3+Fe_2O_3+TiO_2)$				no	Darmody et al. (2005)
Mobiles Index Imob	Mob= (K_2O+Na_2O+CaO) Imob= $(Mob_{fresh}-Mob_{weathered})/Mob_{weathered}$				n/a	Ifran (1996), Aristizábal et al. (2005)
CaO/ZrO ₂	CaO/ZrO ₂			decrease	n/a	Beavers et al. (1963)

APPENDIX 2. SIMPLE WEATHERING INDEX (SWI)

Simple weathering index for rock-pile material (including rock fragments and matrix) at the Questa mine (McLemore et al., 2008a).

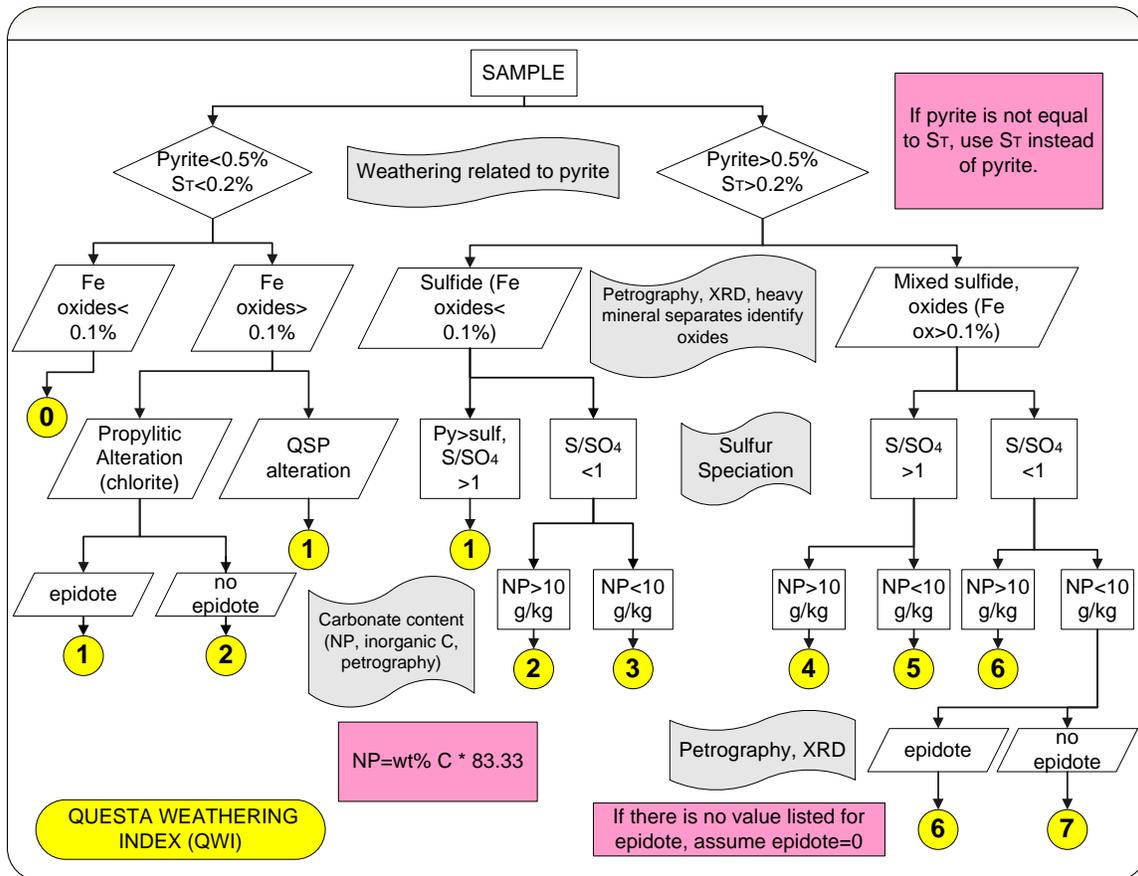
SWI	Name	Description
1	Fresh	Original gray and dark brown to dark gray colors of igneous rocks; little to no unaltered pyrite (if present); calcite, chlorite, and epidote common in some hydrothermally altered samples. Primary igneous textures preserved.
2	Least weathered	Unaltered to slightly altered pyrite; gray and dark brown; very angular to angular rock fragments; presence of chlorite, epidote and calcite, although these minerals not required. Primary igneous textures still partially preserved.
3	Moderately weathered	Pyrite altered (tarnished and oxidized), light brown to dark orange to gray, more clay- and silt-size material; presence of altered chlorite, epidote and calcite, but these minerals not required. Primary igneous textures rarely preserved.
4	Weathered	Pyrite very altered (tarnished, oxidized, and pitted); Fe hydroxides and oxides present; light brown to yellow to orange; no calcite, chlorite, or epidote except possibly within center of rock fragments (but the absence of these minerals does not indicate this index), more clay-size material. Primary igneous textures obscured.
5	Highly weathered	No pyrite remaining; Fe hydroxides and oxides, shades of yellow and red typical; more clay minerals; no calcite, chlorite, or epidote (but the absence of these minerals does not indicate this index); angular to subround rock fragments

The SWI accounts for changes in color, texture, and mineralogy due to weathering, but it is based on field descriptions. Some problems with this weathering index are:

- It is subjective and based upon visual field visual characteristics of the soil matrix, particularly color, presence or absence of igneous textures, cementation, and presence or absence of pyrite, calcite, jarosite, and gypsum.
- This index does not always enable distinction between pre-mining supergene hydrothermal alteration and post-mining weathering.
- The index is developed from natural residual soil weathering profiles, which typically weathered differently from the acidic conditions within the Questa rock piles and, therefore, this index may not adequately reflect the weathering conditions within the rock piles.
- This index refers mostly to the soil matrix; most rock fragments within the sample are not weathered except perhaps at the surface of the fragment and along cracks.
- The index is based primarily upon color and color could be indicative of other processes besides weathering intensity.
- This index was developed for the Questa rock piles and may not necessarily apply to other rock piles.
- Weathering in the Questa rock piles is an open not a closed system (i.e. water analysis indicates the loss of cations and anions due to oxidation).

APPENDIX 3. QUESTA MINERALOGICAL WEATHERING INDEX (QMWI)

The QMWI is a quantified index that ranges from 0-7 (0 is least weathered and 7 is most weathered) and accounts for changes in the pyrite-calcite-gypsum system that is the most predominant weathering system at Questa. The Questa Mineralogical Weathering Index is a measure of the short-term mineralogical changes with the rock pile material (McLemore et al., 2008c; DRA-16). The following flow chart describes the various classes of QMWI.



APPENDIX 4. ADDITIONAL FIGURES

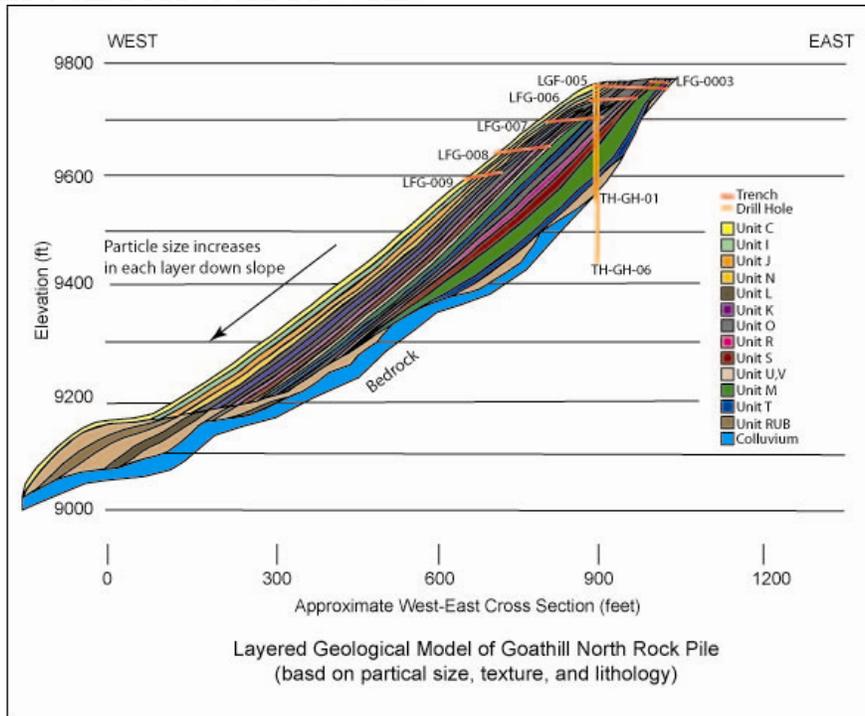


FIGURE 4-1. Conceptual geological model of GHN rock pile, as interpreted from surface mapping, detailed geologic cross section (McLemore et al., 2008a, fig. 26), trenches, drill holes, construction method, and observations during regrading of GHN (McLemore and the Questa Rock Pile and Stability Team, 2008).

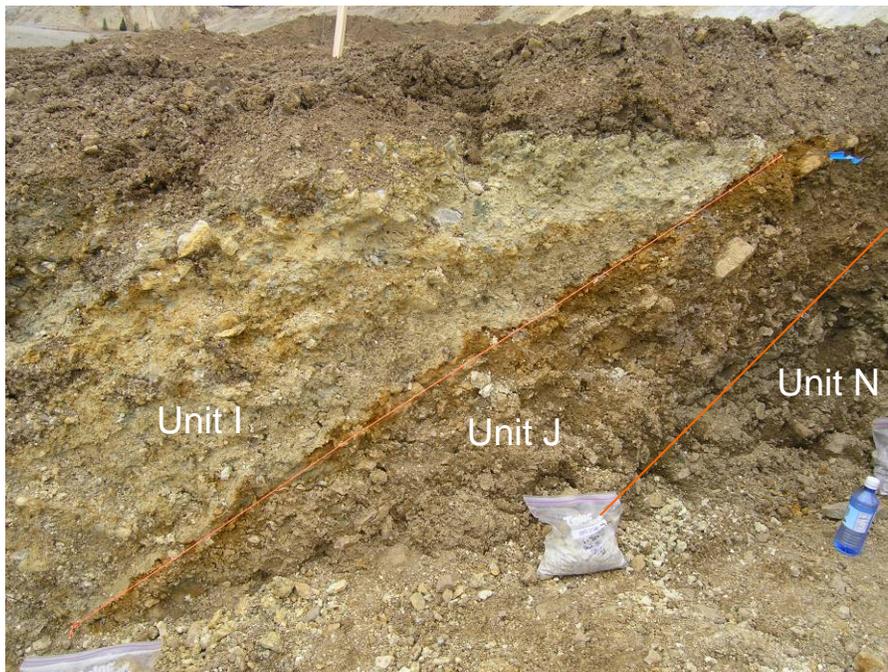


FIGURE 4-2. Contact between units I, J and N in trench LFG-006, GHN showing change in colors (McLemore et al., 2008a).

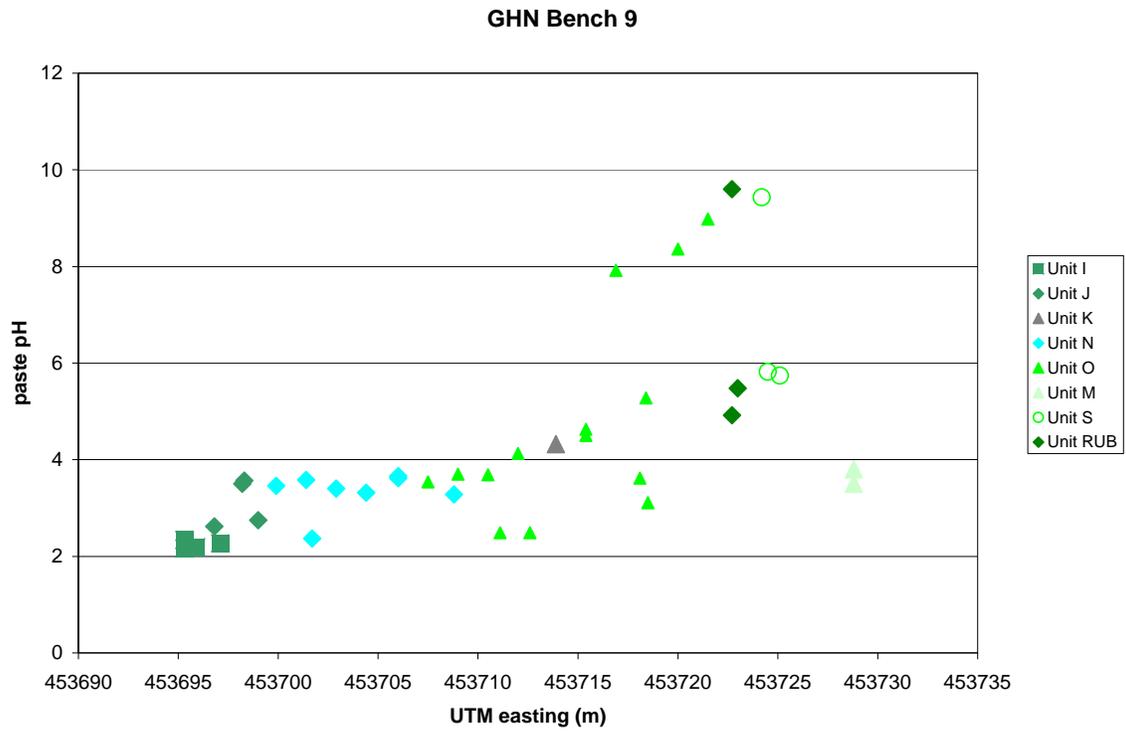
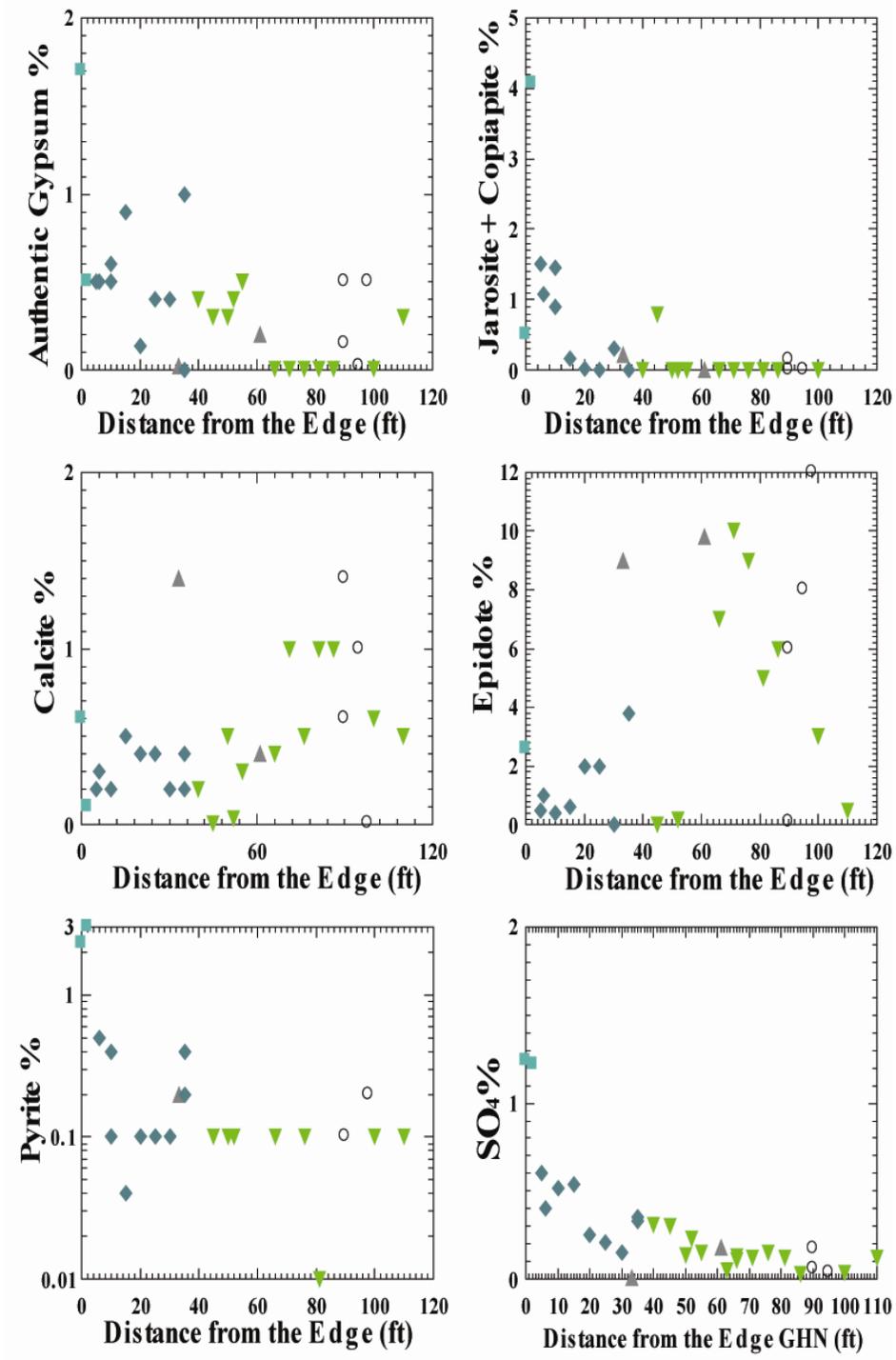


FIGURE 4-3. Paste pH across bench 9, trench LFG-006. Symbols in the graph refer to geologic units in McLemore et al. (2008a, table 20 and figure 43). This graph indicates an increase in paste pH from the outer, oxidized units towards the less weathered, interior of the rock pile.



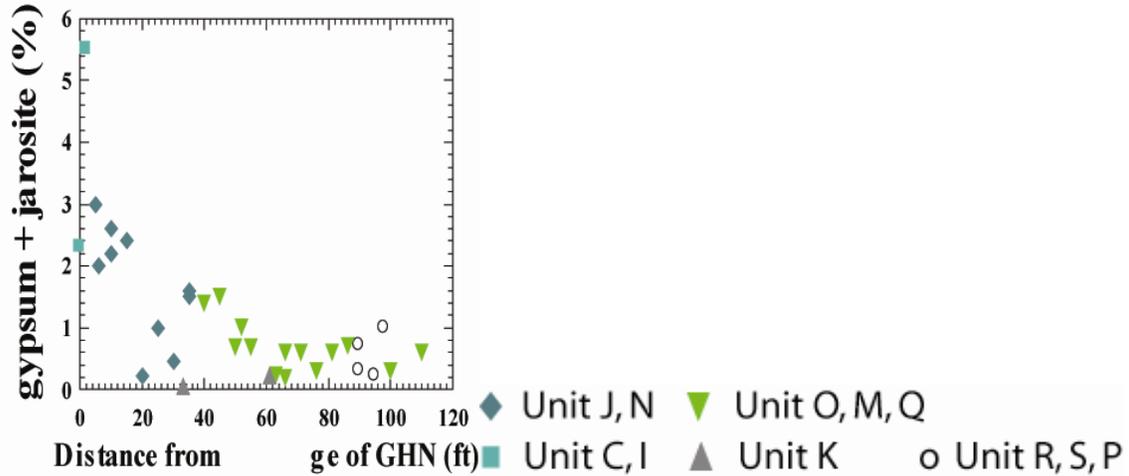


FIGURE 4-4. Variations in authigenic gypsum, jarosite, calcite, epidote, pyrite, and SO₄ in weight percent across bench 9, GHN. More weathered samples (units I, J, N) on the outside of the rock pile (left side of diagram) have slightly higher concentrations of authigenic gypsum. The difficulty in determining the abundances of detrital and authigenic gypsum is that much of the gypsum is too small to properly identify by petrographic techniques. See McLemore et al. (2008a, figure 43) for geologic section and to McLemore et al. (2008a, table 20 for description of geologic units. Mineral abundances were obtained from the modified ModAn technique (McLemore et al., 2009) using whole chemical analyses, SO₄, and S. Pyrite abundances were obtained from modified Reitveld method (Oeter et al., 2007).

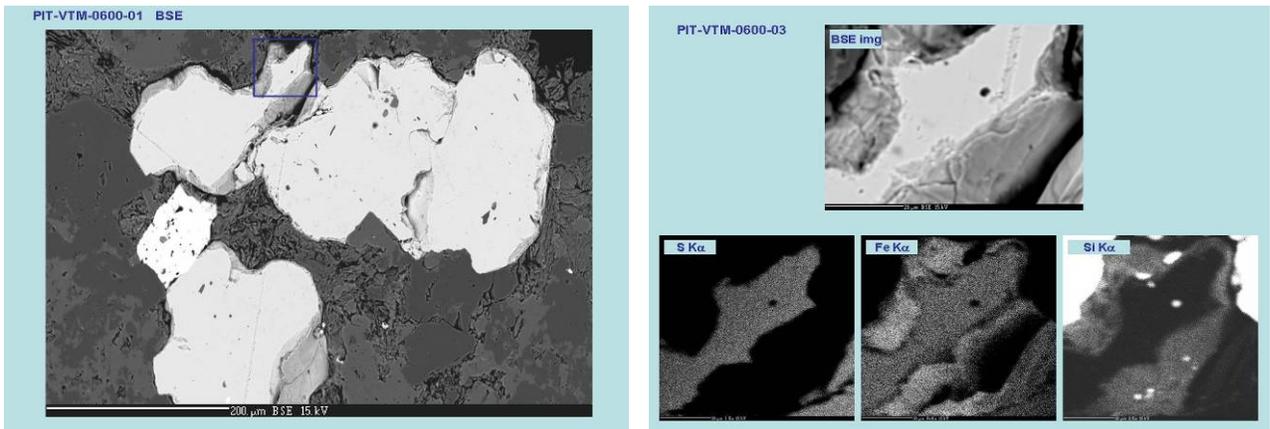


FIGURE 4-5. Backscattered electron image of pyrite grains showing thin tarnish. b) Backscattered electron image and corresponding S, Fe, and Si chemical maps. Scale bar=20 μ (McLemore et al., 2008a).

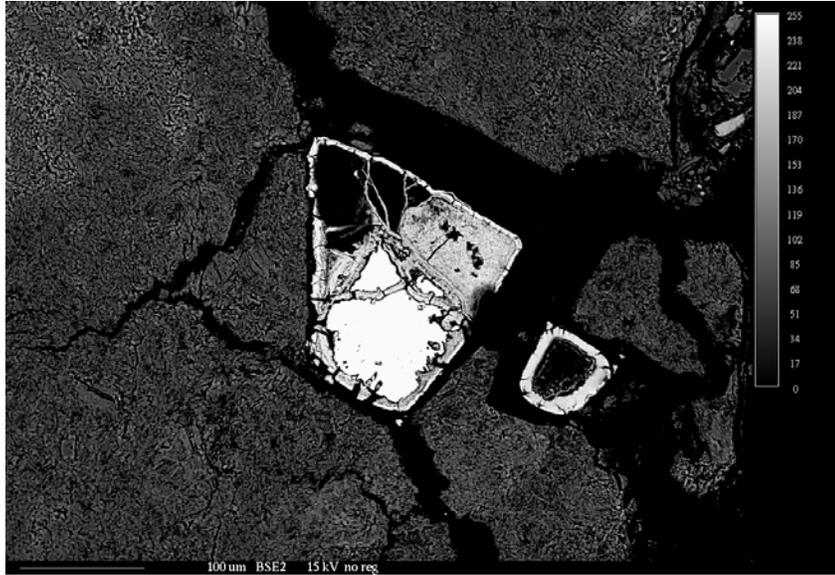


FIGURE 4-6. Oxidation of pyrite (back-scattered electron microprobe image of sample GHN-KMD-0074-30-02, Unit U).



FIGURE 4-7. Boulder of andesite that fell apart along veins and fractures filled with pyrite, partially altered to jarosite and Fe oxides, gypsum, and calcite. This is a result of physical weathering.

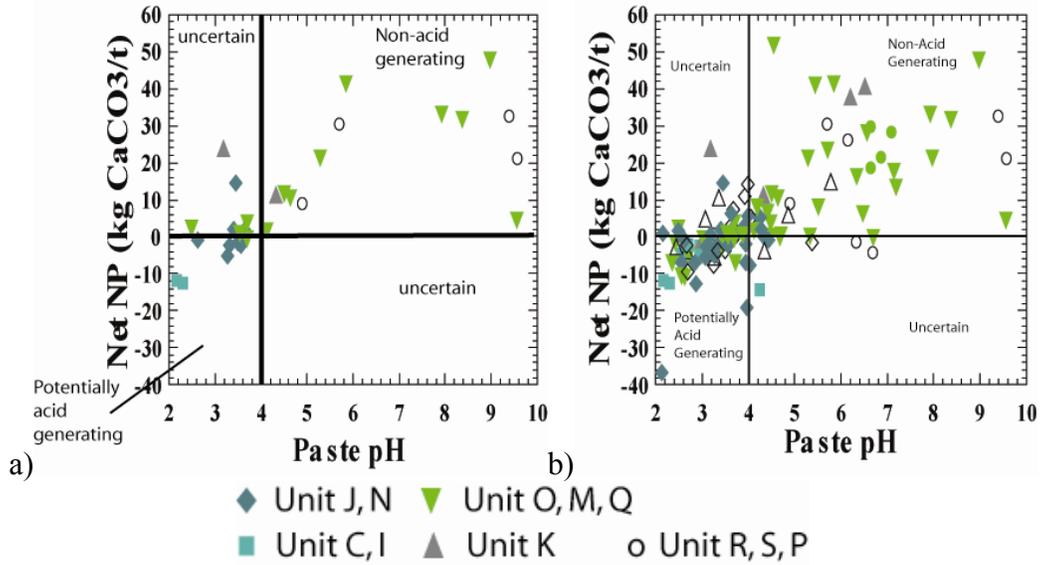


FIGURE 4-8. Net NP (neutralizing potential) versus paste pH for samples a) along bench 9, GHN and b) for all samples in GHN. Geologic units described in McLemore et al. (2008a, table 20).

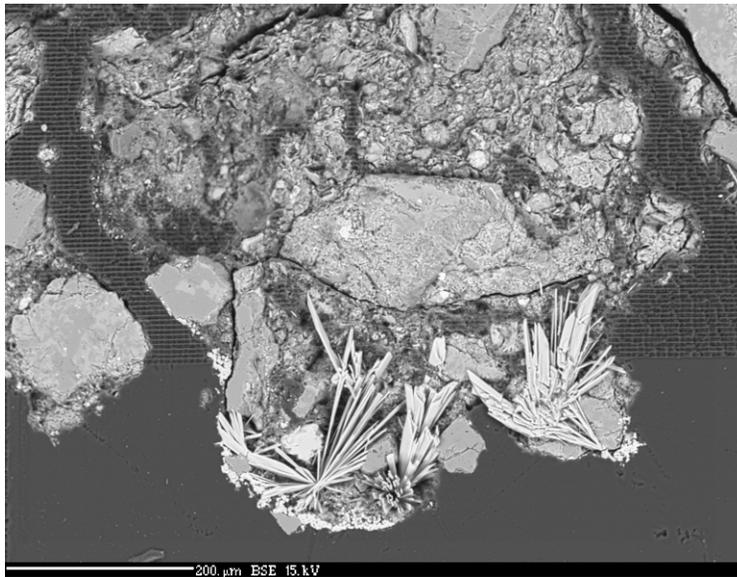


FIGURE 4-9. Gypsum crystals cementing a portion of the matrix material in GHN rock pile (back-scattered electron microprobe image of sample, GHN-JRM-0006-30-02, Unit O).

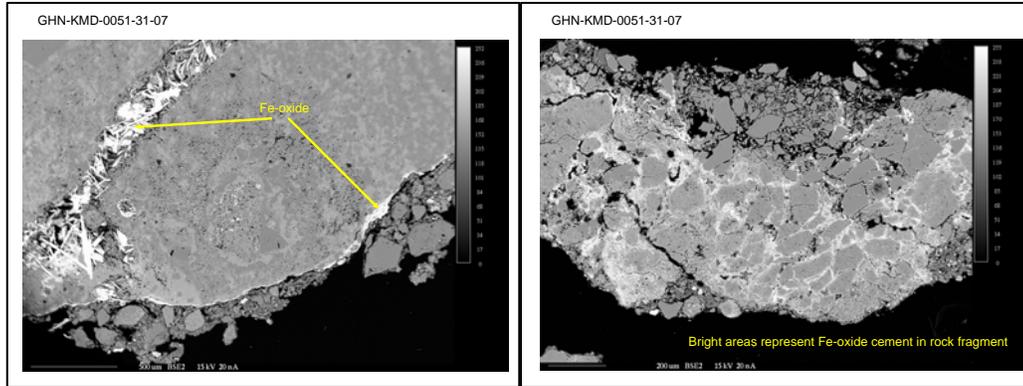


FIGURE 4-10. Iron oxide minerals cementing rock fragments in the GHN rock pile material (back-scattered electron microprobe image)

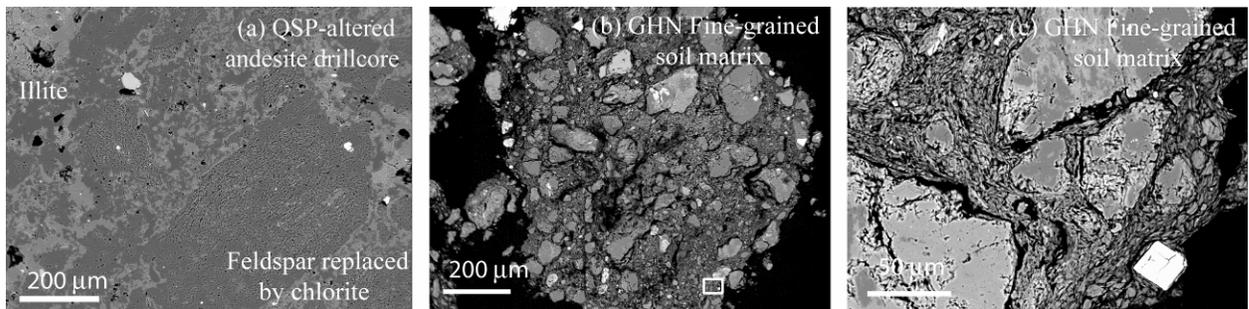


FIGURE 4-11. (a) BSE images of QSP-altered andesite drill core, (b) fine-grained soil matrix samples from GHN rock pile, (c) the magnification of the fine-grained soil matrix sample outlined by the white box in figure 4-10b. From DRA-3.

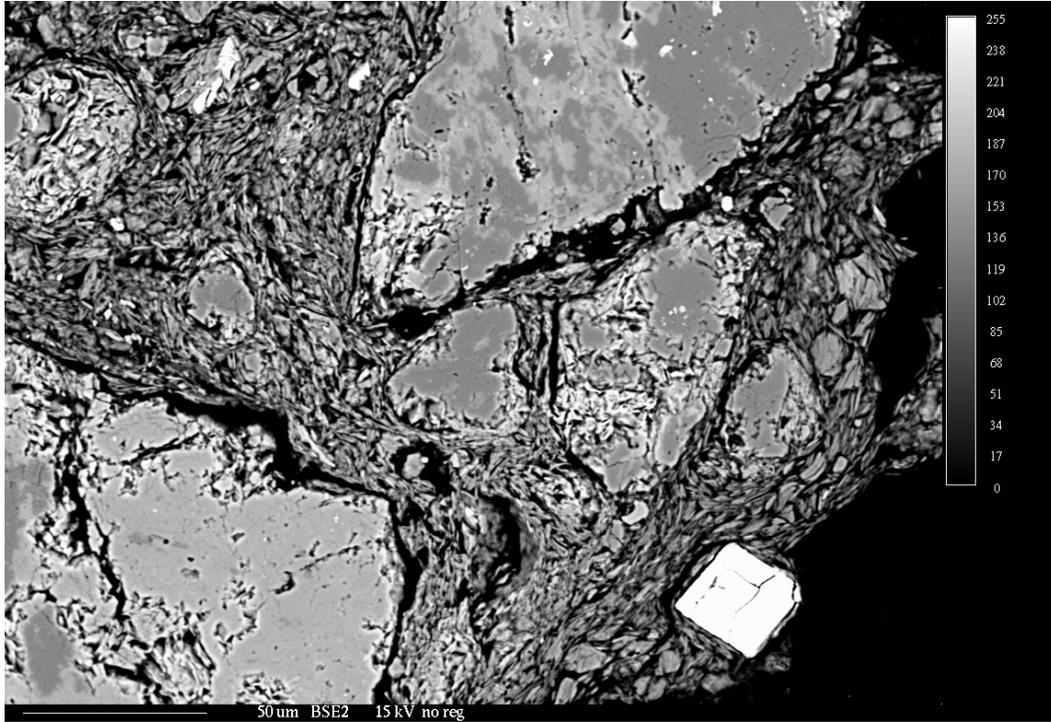


FIGURE 4-12. Back-scattered electron image of GHN-NWD-0019 showing chlorite and illite surrounding and draped around rock clasts and mineral grains. The clay minerals are the “felted” looking areas between the smoothly-polished rock and mineral clasts. The brightness scale is relative to the atomic number of the material with the brighter areas representing higher atomic number. Lower magnification image is in Figure 4-10c.

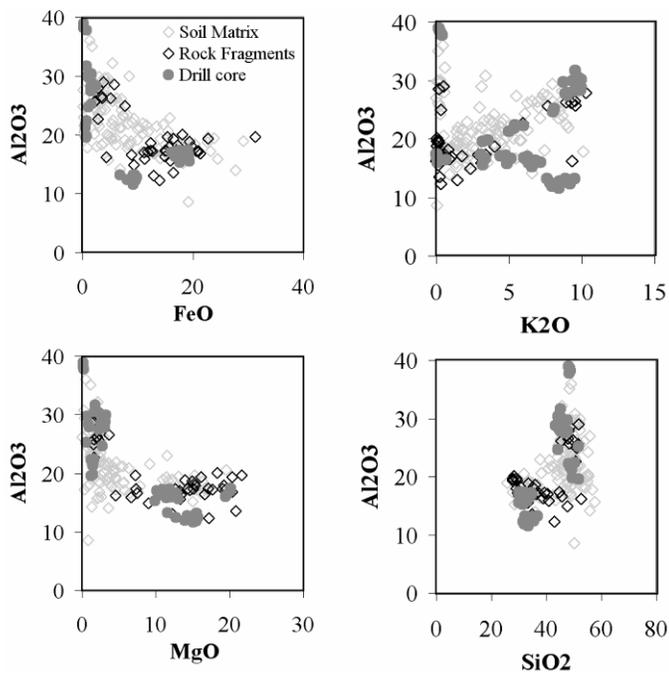


FIGURE 4-13. Scatter plots of mineral chemistries of clay minerals determined using quantitative electron microprobe analysis for GHN fine-grained soil matrix samples (open gray diamond), rock fragments (open black diamonds) and unweathered, drill core samples (filled gray circles).

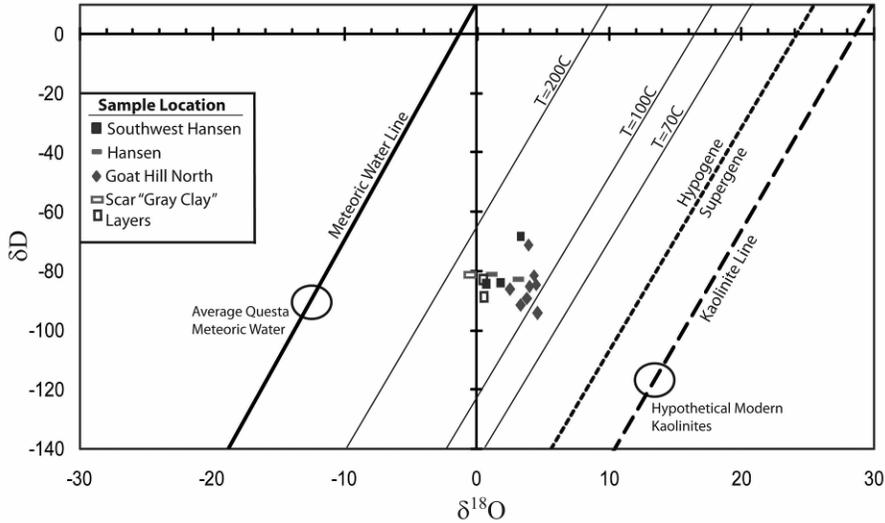


FIGURE 4-14. $\delta D-\delta^{18}O$ diagram for clay minerals from rock pile and alteration scar (Graf, 2008). These clays plot in the hypogene field, indicating an origin consistent with hydrothermal alteration. There is no isotopic evidence that clay minerals formed as a result of weathering in either the alteration scars or the rock piles.

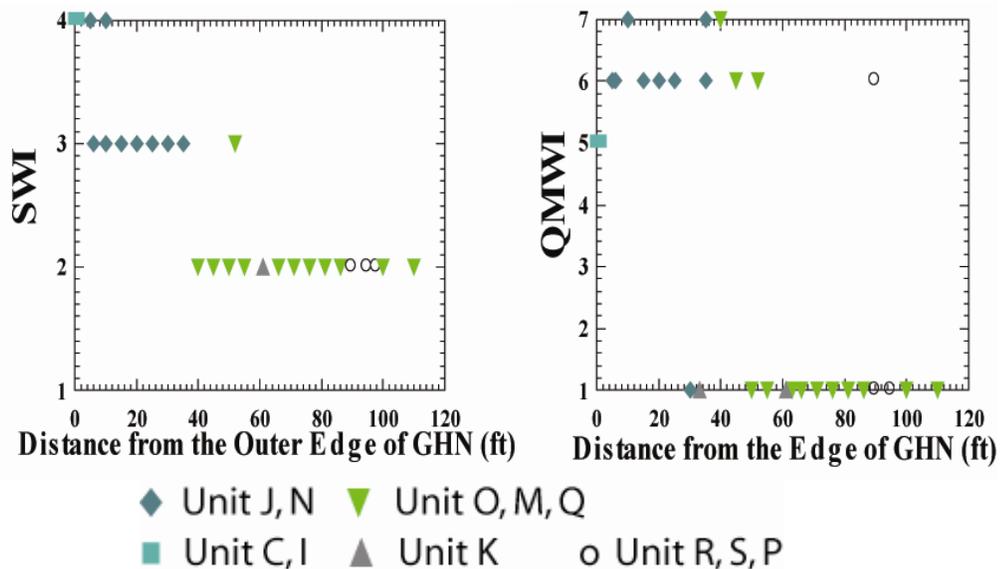


FIGURE 4-15. Variation of SWI (Simple Weathering Index) and QMWI (Questa Mineralogic Weathering Index) along bench 9, GHN. See McLemore et al. (2008a, figure 43) for the geologic section and McLemore et al. (2008a, table 20) for description of geologic units.

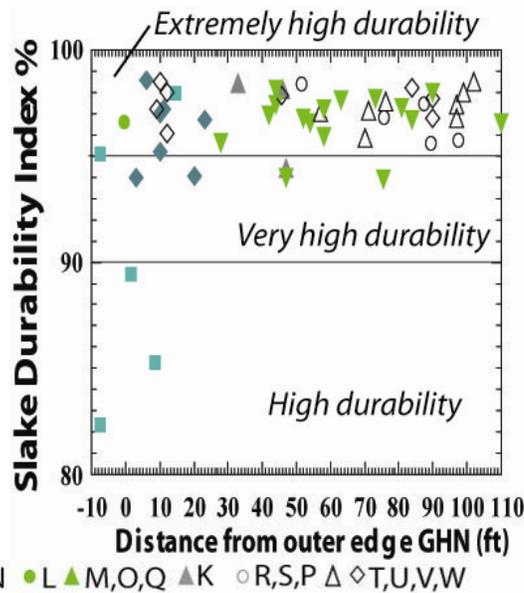
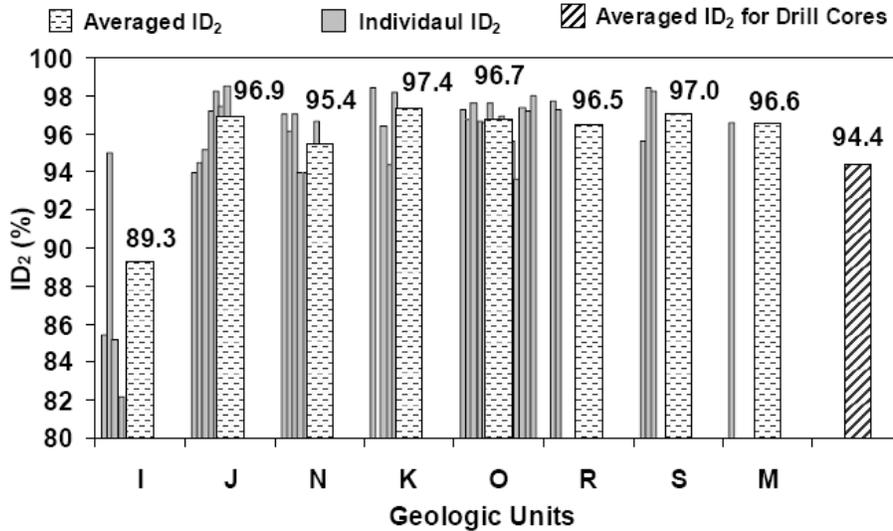


FIGURE 4-16. Bar graph and distance from edge of GHN plots of slake durability index (ID₂) by geologic unit, GHN. The oxidized samples (unit I) tend to have lower slake durability indices than samples from the inner units of the rock pile. Drill core samples are unweathered samples of the open pit deposit before mining (Viterbo, 2007; McLemore et al., 2008a).

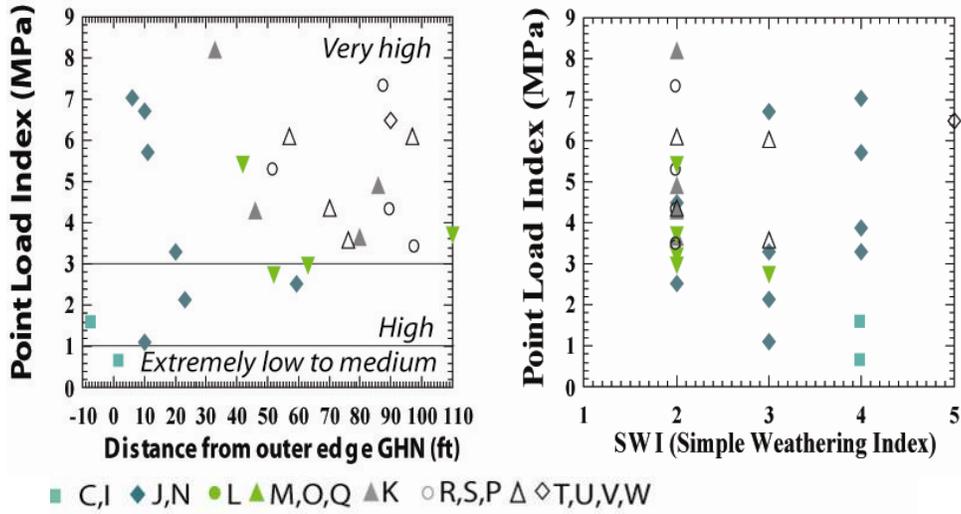


FIGURE 4-17. Variations in point load index for geologic units and SWI for samples from GHN. See McLemore et al. (2008a, table 20) for descriptions of the geologic units.