DRA-21. NATURAL WEATHERING PROFILES IN WEATHERED BEDROCK AS AN ANALOG FOR FUTURE WEATHERING OF ROCK PILES

V.T. McLemore, September 19, 2008, revised December 31, 2008 (reviewed by A. Campbell)

1. STATEMENT OF THE PROBLEM

Can weathered bedrock serve as physical, mineralogical, chemical and geotechnical analogs or proxies to long-term weathering of the rock piles? The extent of weathering in the rock piles is limited by their short exposure history. Processes operating in the weathered bedrock profiles share many similarities to those in the rock piles, although certain aspects of the physical and chemical system are different. Study of natural bedrock weathering profiles can expand the time frame to document greater development of weathering products.

2. PREVIOUS WORK

One method of studying the effects of weathering is by using weathering profiles (Dearman, 1976). *Weathering profiles* consist of a vertical assemblage of layers of basal bedrock and weathered bedrock that could be covered by soil and develops due to chemical, physical, and biological weathering processes occurring at the Earth's surface (Little, 1969; Summerfield, 1991; Anderson et al., 2002; Ehlen, 2005; McLemore, 2008). The process forming weathering profiles involves a downward propagation of a weathering front over time. This weathering front refers to "the three-dimensional boundary surface that separates altered (decomposed or disintegrated) and fresh rock" (Mignon and Lidmar-Bergstrom, 2001, p. 288) and the weathering front will fluctuate up and down according to changes in climatic conditions, primarily precipitation, infiltration, and evapotranspiration. Sampling from the base to the top of the Questa weathering profile demonstrates the progressive change of original, primary igneous minerals and secondary hydrothermal alteration minerals to the formation of tertiary, weathered minerals. The primary texture of the hydrothermally-altered rock material before weathering, which includes fracture patterns, fabric, foliation, veins, etc., can be preserved through most of the profile, even though weathering has transformed the original rock. More details of the bedrock weathering profile are in McLemore (2008).

3. TECHNICAL APPROACH

Trenches were constructed in the bedrock beneath the Goathill North (GHN) rock pile during reclamation. Several of these trenches exposed a weathering profile with unweathered, but hydrothermally altered andesite at the base progressing upwards to more weathered rock material that was overlain by the rock pile. One of these profiles (trench LFG-019, bench 42, UTM easting 453661.5, northing 4062434, zone 13) was selected for detailed analysis to better understand the long-term weathering processes in the Questa area. Detailed mineralogical, geochemical, and geotechnical studies of a weathered profile in weathered bedrock documents physical, chemical, and geotechnical changes in a residual weathering environment in a semi-arid climate. These changes are likely similar to what is expected in the rock piles in the future. The bedrock weathering profile selected is similar in mineralogy, lithology, alteration, and weathering processes to that in the rock piles and is beneath the GHN rock pile (McLemore et al., 2008). The profile represents progressive weathering from weathered bedrock down to fresh bedrock at the base. All profile samples were analyzed similarly to the rock pile samples to assure data consistency between natural analogs and the rock-pile materials. Details of the sampling and analytical analyses are in McLemore (2008).

4. CONCEPTUAL MODEL(S)

In pyrite-bearing silicate rocks, weathering can be divided into two geochemical systems; pyrite-calcite→gypsum-jarosite weathering and dissolution of silicate minerals. Predominant reactions involve the oxidation of pyrite, dissolution of carbonate, and formation of sulfate, mainly gypsum and jarosite (depending on pH):

- Pyrite + Oxygen + Water + Carbonate → gypsum + CO_2 (pH > 3)
- Pyrite + Oxygen + Water → jarosite (pH < 3)

Silicate weathering in an acid environment will be dominated by congruent and incongruent dissolution. The changes in the silicate system require study of rocks that have endured longer weathering histories such as those present in the weathered bedrock. In time, long-term weathering of clay minerals will alter original hydrothermal clay minerals with time, which can affect cementation, cohesion and slope stability. Different clay mineral groups have different geotechnical properties. Surface- and ground-waters contain significant amounts of dissolved Al, Si, Ca, and SO_4 suggesting significant dissolution of silicate phases. However, the architecture of the weathering analogs is initially different from that in the rock piles (DRA-19). The bedrock weathering profile is mineralogically similar to the Questa rock piles (McLemore, 2008; DRA-19), although residual weathering occurs in the profile with little physical transport of material. Natural analogs provide a practical way to study future weathering of the rock piles that can be tested directly by geotechnical methods.

5. STATUS OF COMPONENT INVESTIGATION

The bedrock weathering profile selected is similar in mineralogy, lithology, alteration, and weathering processes to that in the Questa rock piles and consists of hydrothermally-altered, fractured andesite (McLemore et al., 2008). The age of the weathering profile is uncertain, but it was weathered before the rock piles were emplaced. Figure 1 shows the location of the profile and Figure 2 shows a view of the profile looking down into the trench.

The trench was approximately 15 ft deep and consisted of an upper layer of 7.5 ft of basal rock-pile material (not part of the residual weathering profile) and a lower layer of 7.5 ft of weathered bedrock and bedrock (the weathering profile) that was subdivided into four additional layers based upon color, fabric, and texture (McLemore, 2008, table 5). In both outcrop and hand specimen scale, the color of the rock material changed from gray to dark gray black (typical of hydrothermally altered andesite) at the base of the profile to brown at the top of the profile (McLemore, 2008, fig. 3, 4).

Weathering textures increase upwards through the profile (McLemore, 2008). Fe-oxide minerals rim pyrite and chlorite crystals and coat rock fragments at the top of the profile (McLemore, 2008, figs. 7, 8, 9). Epidote crystals are relatively unaltered in the andesite at the base of the profile (McLemore, 2008, figs. 5, 6) and become smaller and are replaced by Fe-oxide minerals towards the top of the profile. Chlorite is relatively fresh in the andesite at the base of the profile (McLemore, 2008, fig. 6) and becomes rimed and partially replaced with Fe-oxide minerals towards the top of the profile (McLemore, 2008, figs. 7, 8, 9). Pyrite crystals are relatively unaltered in the andesite at the base of the profile; whereas pyrite crystals towards the top of the weathering profile exhibit dissolution skeleton textures and are replaced by Fe-oxide minerals (McLemore, 2008, fig. 11, 13). Cementation is variable in the profile (McLemore, 2008, table 5) and is attributed to the precipitation of gypsum, jarosite, soluble efflorescent salts, and Fe oxide/hydroxide minerals (McLemore, 2008, fig. 8, 9).

The oxidation (i.e. weathering) of pyrite and dissolution of calcite to precipitate gypsum, jarosite, soluble efflorescent salts, and Fe oxide/hydroxide minerals is evident in the LFG-019 weathering profile. The percentage of FeO and Fe-oxide minerals increases towards the top of the weathering profile (McLemore, 2008, fig. 2). The percentage of sulfate minerals (jarosite + gypsum) and SO_4 increase towards the top of the profile; whereas calcite decreases towards the top of the profile (Fig. 3). Pyrite is found throughout the profile, but pyrite is more abundant in sample GHN-VTM-0599 in the middle of the profile, which suggests that pyrite was originally higher in that sample than the other samples and it is uncertain how pyrite changes with weathering.

The effects of silicate weathering are not as obvious in the petrographic and electron microprobe analyses. The abundance of feldspar and epidote decreases towards the top of the profile (McLemore, 2008, fig. 16), but large-scale dissolution textures of these silicates are absent, although replacement by Fe-oxide minerals does occur locally. However, the dissolution of these silicate minerals is not readily observed at the scale of electron microprobe analysis. The percent of clay minerals and the Plastic Limit increases towards the top of the weathering profile and the profile becomes finer in particle size towards the top of the profile (McLemore, 2008, figs. 4, 17, 18). The chemical plots (McLemore, 2008, fig. 18) suggest that clay minerals (specifically illite; McLemore, 2008, table 3) are increasing towards the top of the profile and could be related to weathering. However, at Questa isotopic and mineralogical studies have shown that illite is a hydrothermal mineral and not a weathering mineral in the short-term weathering system in the Questa materials (Donahue et al., 2007; Graf, 2008). It is likely that illite, like pyrite, represents a change due to differences in hydrothermal alteration and not weathering. This is consistent with other aspects of the Questa study, including the results of weathering profiles in the alteration scars and isotopic analyses of clay minerals (Graf, 2008). F, Cu, Pb, and Zn concentrations increase towards the top of the profile corresponding to the increase in clay-mineral concentrations. These elements are more likely a result of hydrothermal alteration and not necessarily weathering, because one would expect that these metals would be leached from the weathered zone, not enriched (McLemore, 2008, fig. 20). The paragenesis is summarized in Figure 5.

The weathering profile samples have high durability and strength, even though the samples in the weathering profile have been hydrothermally altered, weathered, show a decrease in particle size, and an increase in clay minerals. Samples from the profile had high peak internal friction angles between 38º and 42º (Fig. 4, McLemore, 2008), which can, in part, be attributed to the subangular to very angular grain shape (Gutierrez, 2006; Gutierrez et al., 2008). Slake durability index tests classified the samples as very high to extremely high durability. The friction angle and slake durability indices in the profile samples are similar to the friction angle and slake durability indices Questa rock-pile material. The peak internal friction angles of GHN samples are between 42º and 47º and slake durability indices are between 89 to 97%, with all of the samples classified as having high to extremely high durability (Gutierrez, 2006; Viterbo, 2007).

6. RELIABILITY ANALYSIS

The chemical analyses are accurate to within ±5% as determined by duplicate and triplicate analyses and comparison to known internal standards. The mineralogical analyses are estimated to be accurate to within ±10% of the reported value and compare well with other mineralogical techniques (McLemore et al., 2009; DRA-5). See McLemore and Frey (2008) for more details on the quality control and quality assurance precision and accuracy data. The age of the weathering profile is uncertain, but it is older than the rock piles. Additional techniques are required to observe textures of the silicate minerals to determine if dissolution is occurring.

The scientific inferences in this phase of the project include:

- Processes operating in the weathered bedrock are the same as those for the rock piles.
- Rock pile materials will become more like weathered bedrock with time.

The technical and data uncertainties include:

- Only one weathering profile in bedrock was studied.
- Hydrologic and geologic frameworks are different between the weathered bedrock and rock piles.
- The age of the weathered bedrock is unknown, but is older than the rock piles (25-40 yrs).

Resolution of discrepancies in data and uncertainties include:

- The use of SOPs and Quality Assurance procedures ensures that sample-to-sample comparisons for given analytical methods are reliable.
- Even though the same processes have been operating on equivalent starting materials for 300,000-1.8Ma, the mineralogical outcomes in the very old deposits does not show evidence of mineralogical transformations (particularly quantitative formation of clay minerals) that would lead to decreasing shear strength.

7. CURRENT CONCLUSION OF THE COMPONENT

Weathering increases from the base of the Questa weathering profile (LFG-016) to the top of the profile and can be used as an analog or proxy to the weathering of the Questa rock piles. The age of the weathering profile is uncertain, but is older than the rock piles. The predominant chemical weathering system is the oxidation of pyrite (forming H_2SO_4) and dissolution of calcite, which leads to the precipitation of gypsum, jarosite, and Fe-oxides. Paste pH decreases from the base to the top of the weathering profile. The percentage of sulfate minerals (jarosite + gypsum) and SO_4 increase towards the top of the profile; whereas calcite decreases towards the top of the profile. Silicate minerals, especially epidote and feldspar, are replaced by Fe oxides and potentially are dissolved. Similar trends were observed in the weathering profiles in the alteration scar areas (Graf, 2008). Decrease in particle size is evident with increase in weathering and could be due to: 1) initial particle size reduction by hydrothermal alteration and fracturing of the bedrock, 2) freeze-thaw and perhaps thermal contraction/expansion action, and 3) precipitation of gypsum and jarosite. Initially the chemical oxidation of pyrite and calcite, especially along veinlets, begins to break up the rock along these fractures and releases silicate minerals (Ludington et al., 2005). Freeze-thaw and perhaps thermal contraction/expansion enhances this initial breakup of the rocks during weathering, along with the precipitation of gypsum and jarosite along fractures. Decrease in particle size allows for increased chemical oxidation because of the increased surface area due to the smaller particle sizes. A similar decrease in particle size was observed in the weathered profiles in the alteration scars (Ludington et al., 2005; Graf, 2008). Cementation is variable in the profile and is attributed to the precipitation of gypsum, jarosite, and iron oxide minerals. Even though the samples in the weathering profile have been hydrothermally altered, weathered, show a decrease in particle size and an increase in clay minerals, the samples have high durability and strength. Both the friction angle and slake durability index are similar to the Questa rock-pile material and do not change significantly in the profile.

However, not all mineralogical and chemical changes observed in the weathering profile are directly related to post-mining weathering process (pyrite-calcite-gypsum-jarosite system) and some are likely due to changes in pre-mining hydrothermal alteration (i.e. QSP, argillic, propylitic). Pyrite concentration was not the same throughout the profile, probably as a result of hydrothermal alteration and not weathering. The increase in clay minerals towards the top of the weathering profile is a result of the increase in illite and is attributed to changes in hydrothermal alteration zonation, not weathering (Donahue et al., 2007; Graf, 2008). F, Cu, Pb, and Zn concentrations also increase towards the top of the profile and these elements could be a result of hydrothermal alteration and not necessarily weathering, because one would expect that these metals would be leached from the weathered zone, not enriched.

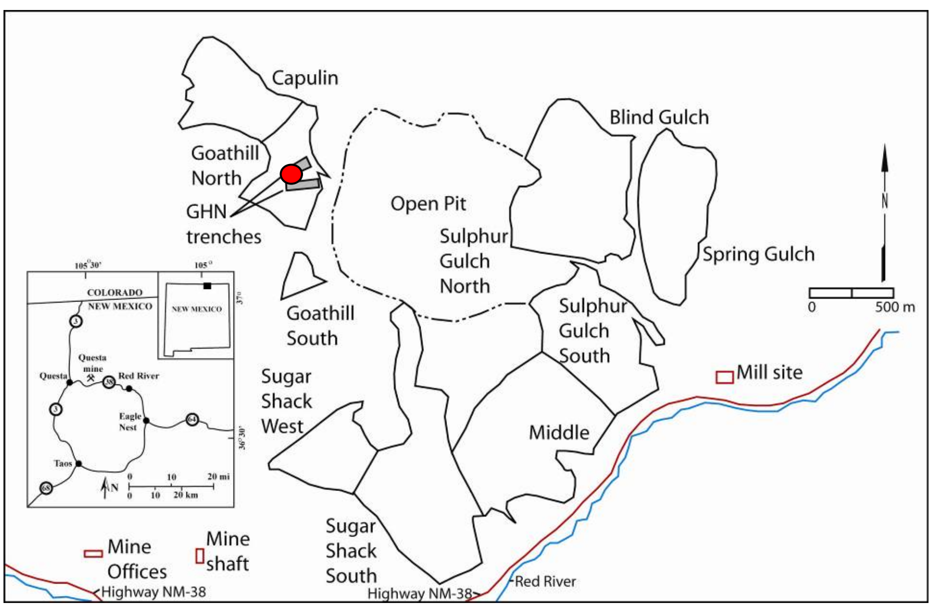

FIGURE 1. Location of Trench LFG-019, bench 42.

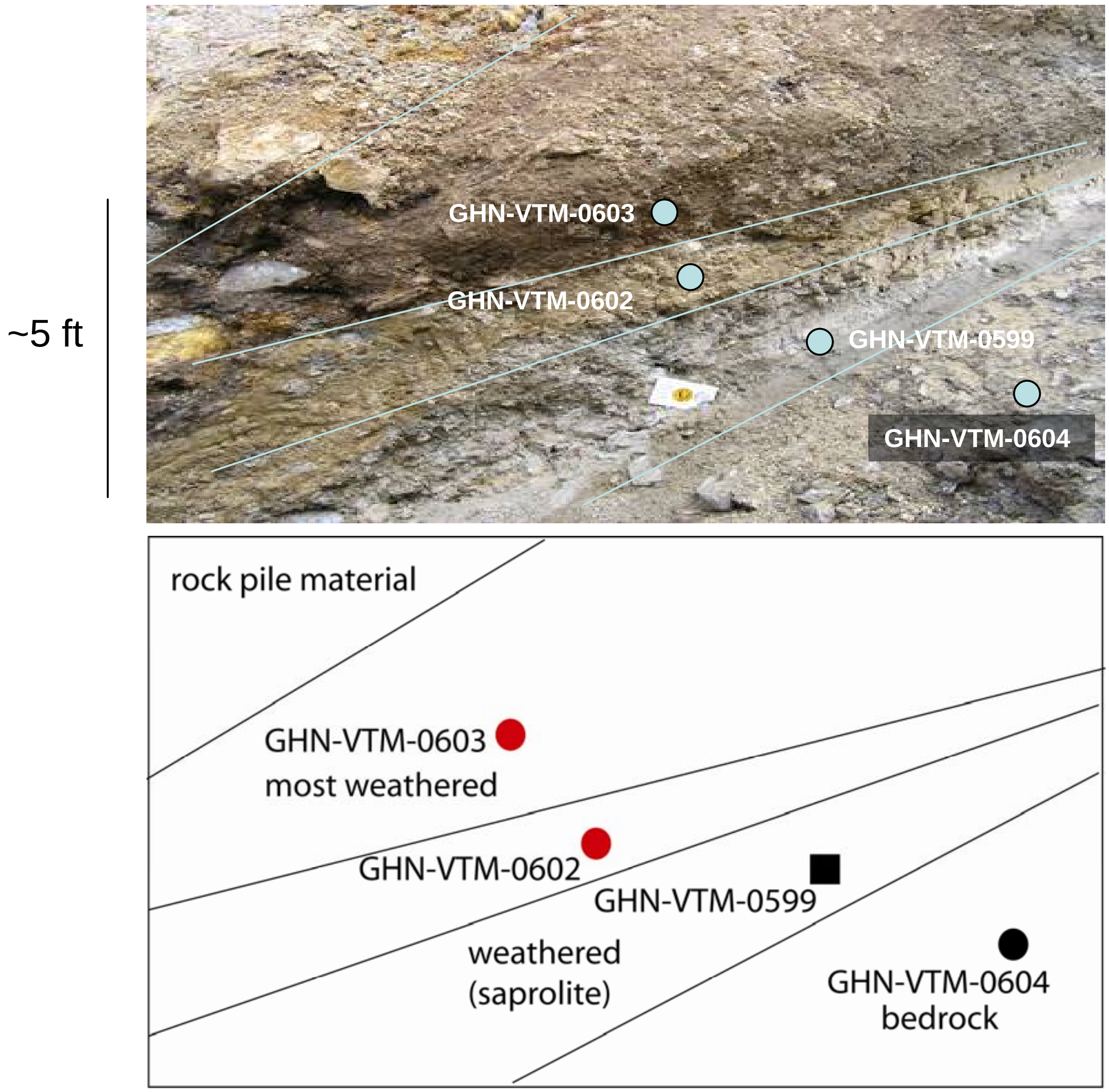

FIGURE 2. Photograph looking down into the trench and descriptive sketch of weathering profile in LFG-019, Bench 42. Scale bar is approximate. Symbols show location of collected samples. Red dots are weathered bedrock, the black square is saprolitic andesite and the black dot is unweathered bedrock. Collected samples consist of a bulk grab of rock material stored in 5 gallon buckets and includes matrix (soil) and rock fragments. The dip of the layers is subparallel to the actual slope where the trench was constructed.

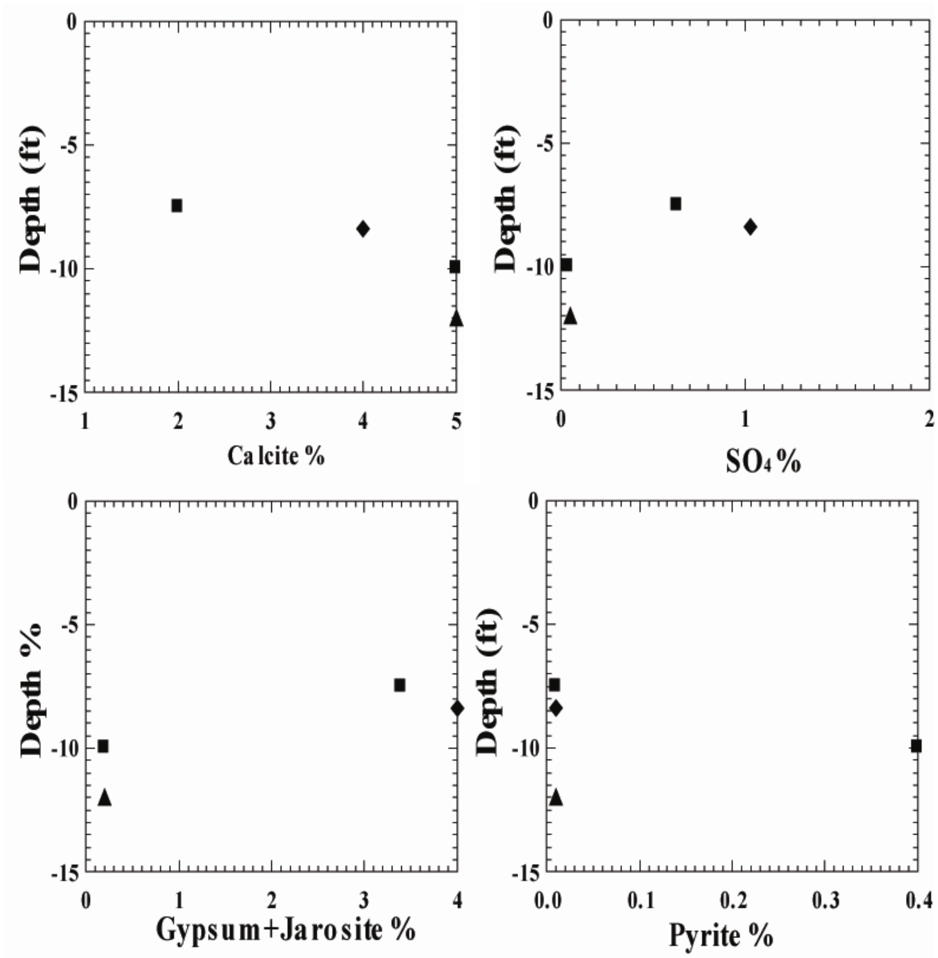

FIGURE 3. Percent calcite, SO_4, gypsum + jarosite, and pyrite with depth in the trench of the weathering profile, showing that calcite decreases towards the top, whereas SO_4 and gypsum + jarosite increases towards the top, suggesting that calcite decreases with weathering and sulfates increases with weathering. However, pyrite is more abundant in one sample.

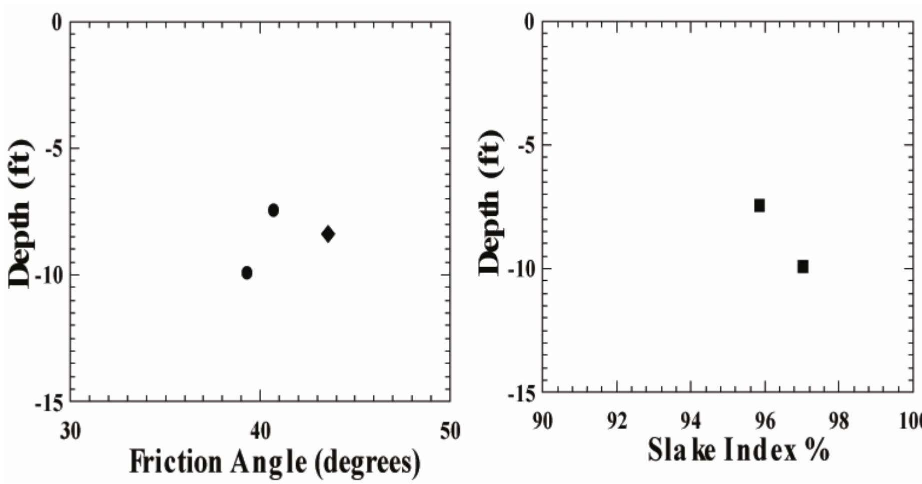

FIGURE 4. Variations in friction angle and slake durability with depth of the weathering profile. Friction angle is determined in the laboratory using high normal stress (160 to 750 kPa) and a 2-inch shear box (Gutierrez, 2006). The samples were air-dried material, passed No. 6 sieve and were compacted to a dry density mostly in the range of 1600-1900 kg/m^3.

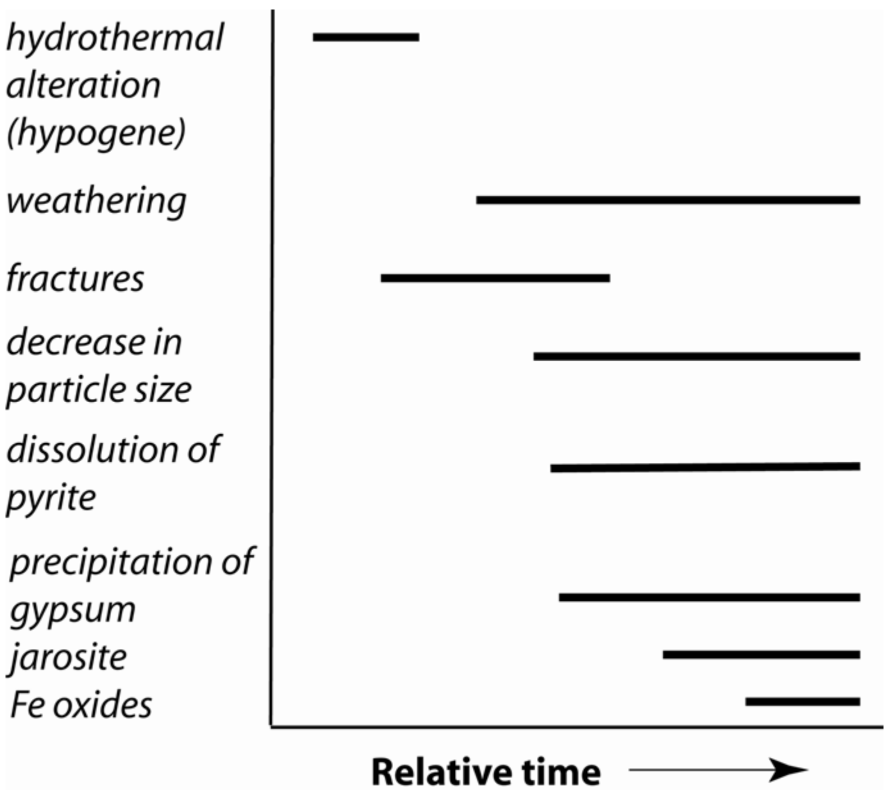

FIGURE 5. Paragenesis of the hydrothermal and weathering alteration of the residual soil profile in trench LFG-019, bench 42, as determined from field observations and petrographic and electron microprobe analyses.

8. REFERENCES CITED

Anderson, S.P., Dietrich, W.E., and Brimhall, G.H., Jr., 2002, Weathering profiles, mass-balance analysis, and rates of solute loss: Linkages between weathering and erosion in a small, steep catchment: Geological Society of America, Bulletin, v. 114, no. 9, p. 1143-1158.

Dearman, W.R., 1976, Weathering classification in the characterisation of rock: a revision: Bulletin of the international Association of Engineering Geology, no. 13, p. 123-127.

Donahue, K.M., Dunbar, N.W., and McLemore, V.T., 2007, Origins of clay minerals in the Molycorp Mine Goathill North Rock pile, Questa NM: Society of Mining, Metallurgy and Exploration Annual Convention, Denver, Feb 2007, no. 07-100, 8 p.

Ehlen, J., 2005, Above the weathering front: contrasting approaches to the study and classification of weathered mantle: Geomorphology, v. 67, p. 7-21.

Gutierrez, L.A.F., 2006, The influence of mineralogy, chemistry and physical engineering properties on shear strength parameters of the Goathill North rock pile material, Questa Molybdenum mine, New Mexico: M.S. thesis, New Mexico Institute of Mining and Technology, Socorro, 201 p., http://geoinfo.nmt.edu/staff/mclemore/Molycorppapers.htm, accessed December 06, 2007.

Gutierrez, L.A.F., Viterbo, V.C., McLemore, V.T., and Aimone-Martin, C.T., 2008, Geotechnical and Geomechanical Characterisation of the Goathill North Rock Pile at the Questa Molybdenum Mine, New Mexico, USA; *in* Fourie, A., ed., First International Seminar on the Management of Rock Dumps, Stockpiles and Heap Leach Pads: The Australian Centre for Geomechanics, University of Western Australia, p. 19-32.

Graf, G., 2008, Mineralogical and geochemical changes associated with sulfide and silicate weathering in natural alteration scars, Taos County, New Mexico: M.S. thesis, New Mexico Institute of Mining and Technology, Socorro, 193 p., http://geoinfo.nmt.edu/staff/mclemore/Molycorppapers.htm, accessed April 28, 2008.

Little, A.L., 1969, The engineering weathering classification of residual tropical soils; in Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering, Special Session on the Engineering Properties of Lateritic Soils: Mexico City, p. 1-10.

Ludington, S., Plumlee, G.S., Caine, J.S., Bove, D., Holloway, J.M., and Livo, K.E., 2005, Questa Baseline and Pre-Mining Ground-Water Quality Investigation. 10. Geologic influences on ground and surface waters in the lower Red River watershed, New Mexico. U.S. Geological Survey Scientific Investigations Report 2004-5245, http://pubs.usgs.gov/sir/2004/5245/, accessed 11/8/08.

McLemore, V.T., 2008, Characterization of a weathering profile through bedrock beneath Goat Hill North Rock Pile, New Mexico: unpublished report to Chevron Mining, Inc., Task B1.4, 30 p.

McLemore, V.T., Ayakwah, G., Boakye, K., Campbell, A., Donahue, K., Dunbar, N., Gutierrez, L. Heizler, L., Lynn, R., Lueth, V., Osantowski, E., Phillips, E., Shannon, H., Tachie-Menson, S., van Dam, R., Viterbo, V.C., Walsh, P., and

Wilson, G.W., 2008, Characterization of Goathill North Rock Pile: revised unpublished report to Molycorp, Tasks: 1.3.3, 1.3.4, 1.4.2, 1.4.3, 1.11.1.3, 1.11.1.4, 1.11.2.3, B1.1.1, B1.3.2.

McLemore, V.T. and Frey, B., 2008, Quality control and quality assurance report: unpublished report to Chevron, Task B1.

McLemore, V., Sweeney, D., Dunbar, N., Heizler, L. and Phillips, E., 2009, Determining quantitative mineralogy using a combination of petrographic techniques, whole rock chemistry, and MODAN: Society of Mining, Metallurgy and Exploration Annual Convention, preprint 09-20, 19 p.

Migon, P., and Lidmar-Bergstrom, K.L., 2001, Weathering mantles and their significance for geomorphological evolution of central and northern Europe since the Mesozoic: Earth-Science Reviews, v. 56, 285-324.

Summerfield, M.A., 1991, Global Geomorphology: An introduction to the study of landforms: First Edition, Longman Group Ltd, England, p. 137-146

Viterbo, V., 2007, Effect of premining hydrothermal alteration processes and postmining weathering on rock engineering properties of Goathill north rock pile at the Questa Mine, Taos, New Mexico: M. S. thesis, New Mexico Institute of Mining and Technology, Socorro, NM, 209 p., http://geoinfo.nmt.edu/staff/mclemore/Molycorppapers.htm, accessed March 10, 2008.

9. TECHNICAL APPENDICES

McLemore, V.T., 2008, Characterization of a Weathering Profile Through Bedrock Beneath Goat Hill North Rock Pile, New Mexico: unpublished report to Chevron Mining, Inc., Task B1.4, 28 p.