DRA-19. NATURAL ANALOGS AS PROXIES TO WEATHERING OF THE QUESTA ROCK PILES

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1. STATEMENT OF THE PROBLEM

Can natural alteration scars, debris flows, weathered bedrock and slope colluvium serve as mineralogical and physical proxies to long-term weathering of the rock piles? Processes operating in the natural analogs share many similarities to those in the rock pile although certain aspects of the physical and chemical system are different.

2. PREVIOUS WORK

Chemical weathering throughout the world is based upon the CO_2 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, calcite, and to a lesser extent chlorite, illite, and other silicate minerals are more important chemical reactions that results in 1) dissolution 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 (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 oxidize minerals in and at the surface of the rock pile.

Specific weathering studies in the Questa area include:

- Ludington et al. (2004), Straight Creek Scar Study
- Meyer and Leonardson (1990), Alteration scar paper
- Campbell and Lueth (2006), Phase 1 stable isotope study of scars and rock piles
- Lueth et al. (2008), geochronological study
- Shaw et al. (2003), Background characterization study
- Robertson GeoConsultants (2001), Background study data report
- Roberts et al. (1990), Geology of the Red River district
- Rock pile literature review (McLemore et al., 2008c)
- Characterization of physical and chemical weathering in the rock piles and evaluation of weathering indices for the Questa rock piles (McLemore et al., 2008b)
- Residual soil weathering profiles in alteration scars (Graf, 2008; DRA-20), including Straight Creek (McLemore and Dickens, 2008; DRA-43)
- Residual soil weathering profile in bedrock beneath GHN rock pile (McLemore, 2008a, DRA-21)
- Profile in debris flow (Ayakwah et al., 2008; DRA-22)

3. TECHNICAL APPROACH

- All analog samples were treated and analyzed identically to the rock-pile samples utilizing the same SOPs to assure data consistency between natural analogs to rock-pile materials.
- Detailed mineralogical, geochemical, and isotopic study of residual soil weathering profiles (Fig. 1) in alteration scars and weathered bedrock document long-term mineralogical and physical changes in a residual weathering environment. Scar materials selected for study were petrologically similar to those in the rock piles. The profiles represent progressive weathering from bedrock up to residual soils. These profiles are constrained by age determinations that allow us to calibrate mineralogic changes due to weathering upward through the profiles. Stable isotope analyses of secondary sulfates discriminate between formation by older hydrothermal alteration and formation during subsequent weathering. Stable isotope studies of the clay minerals differentiate between hydrothermal and weathering clays.
- Detailed mineralogical study of the Goat Hill debris flow documents long-term mineralogical and physical changes in another natural environment. The deposition of debris flows represents an analogy to the mining of scar material, redeposition, albeit by water as the transporting fluid phase, and cementation.
- Similar studies in residual soil weathering profiles in weathered bedrock material sections also document changes in environments characterized by in-situ weathering that are more similar to the rock piles with respect to grain size distribution, but only in a single lithology.

FIGURE 1. Residual weathering profile in the lower portion of the Hansen scar. Gabriel Graf (blue hard hat) is at the base of profile, standing on bedrock. Dr. Andrew Campbell (white hard hat) is at the top of the profile standing on fine-grained material. Sample sites

located under red dots–note sampling proceeded bottom to top to avoid sample contamination from above.

4. CONCEPTUAL MODEL

- Phase 1 study of the rock piles and alteration scars identified some modern weathering processes that mainly concern the oxidation of pyrite. Predominant reactions involve the oxidation of pyrite, dissolution of carbonate, and formation of sulfate, mainly gypsum and jarosite (depending on pH) and Fe oxides.
  - Pyrite + Oxygen + Water + Carbonate $\rightarrow$ gypsum + CO_2 (pH > 3)
  - Pyrite + Oxygen + Water $\rightarrow$ jarosite (pH < 3)
- Silicate weathering in an acid environment will be dominated by congruent dissolution.
- Alteration scars represent long-term weathered analogs (300,000 years to 1.8 million year; Lueth et al. 2008) to the same rocks and minerals in the rock piles and should contain products of silicate weathering. Debris flows represent intermediate-term weathering (10 to 100,000 year scale; Lueth et al., 2008), although these materials have been weathered in situ, transported, deposited, and subjected to subsequent weathering. Weathered bedrock material represents long- to intermediate-weathering (older than the rock piles).
- Architecture of the analogs is initially different from that in the rock piles (Fig. 2, Appendix 1):

  The basic geometry and geologic structure of the residual weathering profiles in the alteration scars is different from that of the rock piles:
    - Scar materials consist of regolith derived from igneous rock weathered in place whereas the rock piles are more properly categorized as angular and immature sediments deposited in place.
    - The outer “skin” of the scars undergoes cyclical cementation similar to the outer portions of the rock piles. Authigenic precipitation of minerals is more pronounced in the scar materials.
    - Smaller volumes of detrital material and higher water content in the scars.
    - More uniform grain sizes in the scar material (although spatially variable within an entire weathering profile).
    - Residual weathering occurs in the scars with little physical transport of material within the detrital portion. Surface erosion does remove significant volumes of regolith in the scars.

  The residual weathering profile in bedrock beneath the GHN rock pile is similar in composition and weathering processes to the rock pile (DRA-21). The debris flows are physically more similar to rock piles (Fig. 3, Appendix 1, DRA-22), although the debris flows are transported by water. The analogs are similar to the rock piles in terms of the same climate, rock types, landscape configuration, bedrock configuration, regional groundwater regime.
- Natural analogs provide the only way to study future weathering of the rock piles that can be tested directly by geotechnical methods.

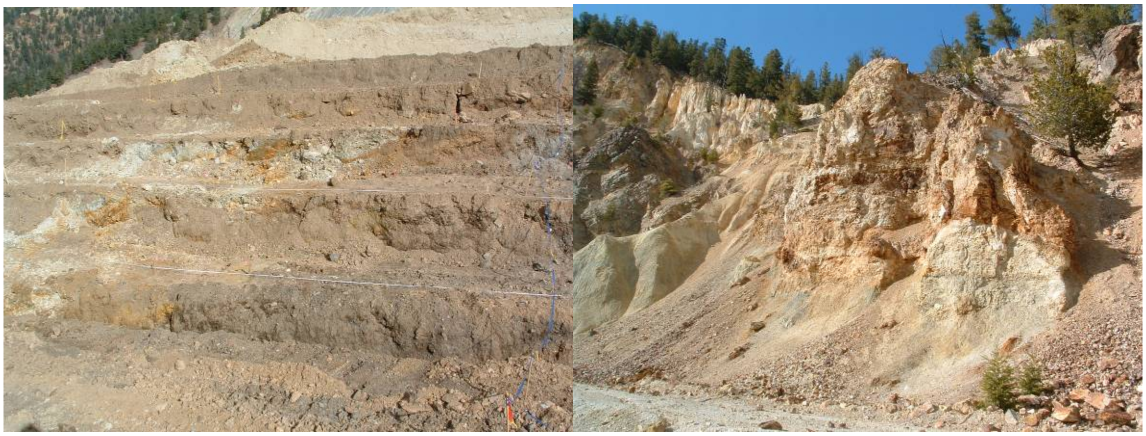

FIGURE 2. Goathill North rock pile (left) and residual scar material in the Questa Pit Scar (right).

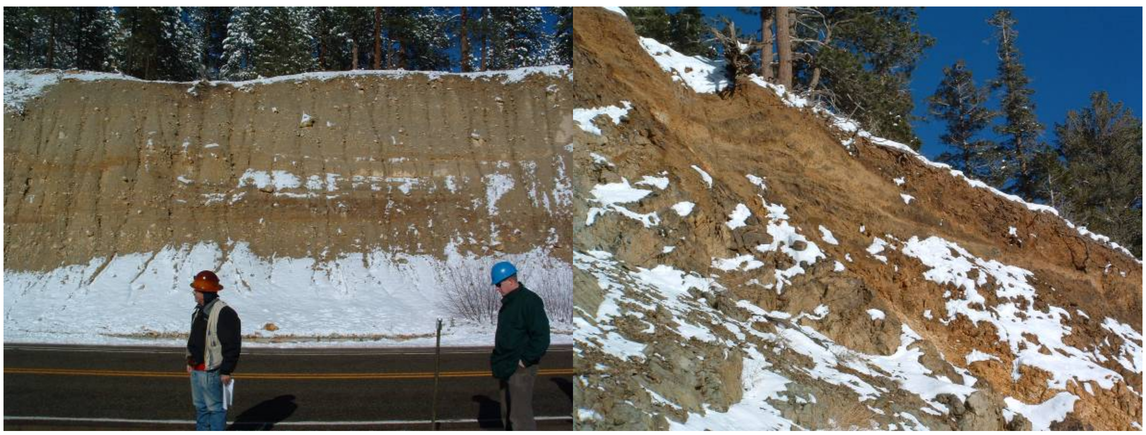

FIGURE 3. Goat Hill debris flow (left) and an example of colluvium at the mine site (right).

5. STATUS OF COMPONENT INVESTIGATION

- Direct comparison of important geologic features can quickly illustrate the similarities and differences between analogs (Appendix 1).
- Isotopic and textural studies documented the mineralogical changes in the short term system (authigenic gypsum forming from oxidation of pyrite coupled with calcite dissolution and/or cation exchange from clays) in the rock piles and natural analogs (Campbell and Lueth, 2006; McLemore et al., 2008b).
- Soil weathering profiles in alteration scars and weathered bedrock that are composed of rocks similar to the rock piles have been identified and sampled (Graf, 2008; McLemore, 2008a).
- Isotopic composition of sulfur and oxygen of authegenic jarosite and gypsum in the profiles and many rock pile samples indicates their origin is by weathering (Campbell and Lueth, 2006, 2008; Graf, 2008).
- Grain sizes generally decrease upward in the selected weathered profiles, however this trend is complicated by hydrothermal alteration patterns and secondary cementation (Graf, 2008).

- Secondary cementation processes, mainly sulfate and iron oxide cement and ferricrete formation, have been identified (Campbell and Lueth, 2008; Ayakwah et al., 2008; Graf, 2008). Sulfate mineral precipitation is also observed in the rock piles (Campbell and Lueth, 2008; McLemore et al., 2008a).
- Clay-rich portions of the scar analog profiles are the product of hydrothermal alteration, which also is the origin of the clay exposed in the rock piles (Graf, 2008). These clay-rich portions are not the product of surficial weathering (Graf, 2008; DRA-3).
- Weathering appears most intense and of longest duration at the tops of weathered profiles (Graf, 2008; McLemore, 2008a).
- The mineralogical outcomes of weathering in the analogs are indistinguishable from the weathering products observed in the rock piles, for equivalent starting rock types and mineralogies. Therefore, the data are consistent with a hypothesis that the same processes are acting in both environments. Also, given that the processes and products are equivalent in the old (>10,000 years old) analogs, there is no support for the idea that clay minerals can be formed in quantitatively important volumes in time periods of 100-1000 years.

6. RELIABILITY ANALYSIS

The scientific inferences in this phase of the project include:

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

The technical and data uncertainties include:

- Limited number of weathering profiles in each analog was studied. Three profiles in two different rock types within the scar analog. Only one profile each in debris flow and bedrock analogs.
- Hydrologic and geologic frameworks are different between the analogs and rock piles.
- Absolute time calibration–geochronological dating only assigns a bracket of ages but the range of ages is so large (up to 1.5 million years in the scar analog), the impact of age uncertainties is small with in the decision-making range of the study (100 to 1000 years).

Resolution of discrepancies in data and uncertainties include:

- The use of SOPs and QA 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 300k-1.8Ma (less for other analogs), 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. CONCLUSION OF THE COMPONENT

- The initial lithology and hydrothermal alteration assemblages of the rock-pile materials, alteration scars, debris flow, and bedrock are similar (McLemore and Dickens, 2008; McLemore, 2008a; Graf, 2008; Ayakwah et al., 2008). Accordingly, alteration scars and bedrock material would provide an accurate analog to mineralogical changes expected in the rock piles over long time frames of weathering, provided the processes are equivalent. Physical analogy in the short term is not exact, but the materials should converge (become more alike) mineralogically with time.

- Sulfate mineralogy, acid-base geochemistry, and grain size of the analog samples indicate conditions of more advanced weathering than rock pile samples, supporting the long-term analog hypothesis.
- Studies have confirmed similar processes are operating within the sulfide-sulfate system between natural scars and the rock piles. Initial work on the debris flows and colluvium/weathered bedrock indicates similar processes within those analogs.
- Geochemical and isotopic studies indicate that silicate dissolution is the predominant silicate weathering process (Graf, 2008; McLemore, 2008a; DRA-20, 21, 22, 26). No authigenic clays have been recognized in any analog or rock pile (DRA-3).
- Formation of new clay minerals by incongruent dissolution of silicates does not appear to be important over long time periods within the analogs.

8. REFERENCES

Ayakwah, G., McLemore, V.T., and Dickens, A., 2008, Characterization of Questa debris flows: unpublished report to Chevron Mining Corporation, Task B1.4.

Campbell, A.R. and Lueth, V.W., 2006, Final Report (Phase I) on the stable isotopic composition of pile and scar samples: Isotopic and textural discrimination between hypogene, ancient supergene, and modern sulfates at the Questa Mine, New Mexico: Molycorp Task 1.13.3, 41 p.

Campbell, A.R. and Lueth, V.W., 2008, Isotopic and textural discrimination between hypogene, ancient supergene, and modern sulfates at the Questa mine, New Mexico: Applied Geochemistry, v. 23, no. 2, p. 308- 319

Drever, J.I., 1997, The Geochemistry of Natural Waters: Surface and Ground water Environments (3rd edition), 436 p. Prentice Hall, New Jersey.

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.

Ludington, S., Plumlee, G., Caine, J., Bove, D., Holloway, J. and Livo, E., 2004, Questa baseline and pre-mining ground water investigation: 10. Geologic influences on ground and surface waters in the Red River watershed, New Mexico: U.S. Geological Survey open-file report 2004-5245, 41 p.

Lueth, V.W. Samuels, K.E., and Campbell, A.R., 2008, Final Report (Phase II) on the geochronological ($^{40}Ar/^{39}Ar$) dating of jarosite and alunite samples from the Red River area alteration scars and debris flows: The timing of alteration scar formation and weathering: Molycorp Task 1.13.5, 18 p.

McLemore, V.T., 2008a, 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., ed., 2008b, Management Technologies for Metal Mining Influenced Water, Volume 1: Basics of Metal Mining Influenced Water: Society for Mining, Metallurgy, and Exploration, Inc., Littleton, CO, 102 p.

McLemore, V.T. and A. Dickens, 2008, Petrographic analysis, mineralogy, and chemistry of UBC geotechnical samples: report to Chevron, Task B1.

McLemore, V.T., Ayakwah, G., Boakye, K., Campbell, A., Dickens, A., Donahue, K., Dunbar, N., Gutierrez, L., Heizler, L., Lynn, R., Lueth, V., Osantowski, E., Phillips, E., Shannon, H., Smith, M., Tachie-Menson, S., van Dam, R., Viterbo, V.C., Walsh, P., and Wilson, G.W., 2008a, 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., Donahue, K., Dunbar, N. and Heizler, L., 2008b, 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.

McLemore, V.T., Fakhimi, A., Ayakwah, G.F., Boakye, K., Anim, K., Ennin, F., Felli, P., Fredlund, D., Gutierrez, L.A.F., Nunoo, S., Tachie-Menson, S., and Viterbo, V.C., 2008c, Literature review of other rock piles: characterization, weathering, and stability: unpublished report to Molycorp Management, Task B4.2.5, 106 p.

Meyer, J. and Leonardson, R., 1990, Tectonic, hydrothermal and geomorphic controls on alteration scar formation near Questa, New Mexico: New Mexico Geological Society, 41st Field Conference Guidebook, p. 417-422.

Price, J. R., 1993, A suggested method for the classification of rock mass weathering by a rating system: Quarterly Journal of Engineering Geology, v. 21, p. 69-76.

Roberts, T.T., Parkison, G.A., and McLemore, V.T., 1990, Geology of the Red River district, Taos County, New Mexico: New Mexico Geological Society, 41st Field Conference Guidebook, p. 375-380.

Robertson GeoConsultants, 2001, Background Study data report, Questa Mine, New Mexico: RGC Report No. 052008/12, 40 p.

Shaw, S., Wels, C., Robertson, A., Fortin, S. and Walker, B., 2003, Background characterization study of naturally occurring acid rock drainage in the Sangre de Cristo Mountains, Taos County, New Mexico: 6th ICARD, p. 605-616.

8. TECHNICAL APPENDICES

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.

McLemore, V.T., Donahue, K., Dunbar, N. and Heizler, L., 2008b, 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. Comparison of the different weathering environments in the rock piles and analog sites in the Questa area. References in parenthesis are the sources for the majority of the parameters listed in the table. See DRA-2 42 and McLemore et al. (2008b) for more details on the statistical analyses. QSP=quartz-sericite-pyrite. SP=poorly-graded sand, GP=poorly-graded gravel, SM=silty sand, SC=clayey sand, GW=well-graded gravel, GC=clayey gravel, GP-GC=poorly-graded gravel with clay, GP-GM=poorly-graded gravel with silt, GW-GC=well-graded gravel with clay, SW-SC=well-graded sand with clay, SP-SC=poorly-graded sand with clay.

Feature	Rock Pile (McLemore et al., 2008a, b)	Alteration Scar (Graf, 2008; McLemore, in preparation)	Debris Flow (Ayakwah et al., 2008)	Colluvium and weathered bedrock (McLemore, 2008b)
Rock types	Andesite Rhyolite Aplite Porphyry Intrusion	Andesite Rhyolite Aplite Porphyry Intrusion	Andesite Rhyolite Aplite Porphyry Intrusion	Andesite Rhyolite

Feature	Rock Pile (McLemore et al., 2008a, b)	Alteration Scar (Graf, 2008; McLemore, in preparation)	Debris Flow (Ayakwah et al., 2008)	Colluvium and weathered bedrock (McLemore, 2008b)
Unified soil classification (USCS)	GP-GC, GC, GP-GM, GW, GW-GC, SP-SC, SC, SW-SC, SM	GP-GC, GP	GP, SP, GP-GC	GP-GC, GP
% fines	0.2-46 Mean 7.5 Std Dev. 6 No of Samples=89	0.6-20 Mean 5.2 Std Dev. 4 No of Samples=18	0.3-6 Mean 1.8 Std Dev. 2 No of Samples=12	3-40 Mean 20 Std Dev. 11 No of Samples=30
Water content (%)	1-24 Mean 10 Std Dev. 4 No of Samples=390	1-20 Mean 9 Std Dev. 4 No of Samples=48	1-29 Mean 5 Std Dev. 4 No of Samples=36	9-26 Mean 14 Std Dev. 3 No of Samples=13
Paste pH	1.6-9.9 Mean 4.8 std dev 1.9 No of samples=1368	2.0-8.3 Mean 4.3 std dev 1.6 No of samples=215	2.0-6.9 Mean 4.5 std dev 1.3 No of samples=58	2.4-8.6 Mean 3.8 std dev 1.3 No of samples=45
Pyrite content (%)	Low to high 0-14% (mean 1.0%; std dev. 1.2%, No of samples=1098)	Low to high 0-11% (mean 0.7%, std dev 1.8%, No of samples=62)	Low to medium 0-0.2% (mean 0.03%, std dev 0.06%, No of samples=22)	Low to high 0-5.1% (mean 0.4%, std dev 1.1%, No of samples 26)
Dry density kg/m^3	1400-2400 Mean 1800 Std Dev. 140 No of Samples=153	1500-2300 Mean 1900 Std Dev. 210 No of Samples=13	1300-2200 Mean 1900 Std Dev. 340 No of Samples=10	2200 No of Sample=1
Particle shape	Angular to subangular to subrounded	Subangular	Subangular to subrounded	Subangular to subrounded
Plasticity Index (%)	0.2-20 Mean 10 Std Dev. 5 No of Samples=134	5-25 Mean 12 Std Dev. 5 No of Samples=30	3-14 Mean 7 Std Dev. 3 No of Samples=18	5-23 Mean 13 Std Dev. 5 No of Samples=17
Degree of chemical cementation (visual observation)	Low to moderate (sulfates, Iron oxides)	Moderate to high (sulfates, Iron oxides)	Moderate to high (sulfates, Iron oxides)	Moderate to high (sulfates, Iron oxides)
Slake durability index (%)	80.9-99.5 Mean 96.6 Std Dev. 3.1 No of Samples=120	64.5-98.5 Mean 89.2 Std Dev. 9.2 No of Sample=24	96.1-99.6 Mean 98.4 Std Dev. 0.9 No of Samples=18	93-98.5 Mean 95.7 Std Dev. 1.7 No. of Samples= 9
Point Load index (MPa)	0.6-8.2 Mean 3.8 Std Dev. 1.7 No of Samples=59	1.7-3.8 Mean 2.8 Std Dev. 0.8 No of Samples=4	2.6-6 Mean 4 Std Dev. 1 No of Samples=12	Not determined
Peak friction angle (degrees), 2-inch shear box (NMIMT data)	35.3-49.3 Mean 42.2 Std Dev. 2.9 No of Samples=99	33.4-54.3 Mean 40.7 Std Dev. 4.8 No of Samples=22	39.2-50.1 Mean 44.3 Std Dev. 3.9 No of Samples=12	36.9-46.1 Mean 41.4 Std Dev. 2.5 No of Samples=22
Average cohesion (kPa), in-situ shear tests	0-25.9 Mean 9.6 Std dev 7.3 No of samples=20	12.1-23.9 Mean 18.1 No of samples=2	31.4-46.1 Mean 38.8 No of samples=2	Not determined