DRA-7. CHARACTERIZATION OF THE LOCAL HOT ZONES FOUND IN THE QUESTA ROCK PILES

V.T. McLemore, K. Donahue, A. Campbell, and A. Dickens March 24, 2008, revised March 30, 2009 (A. Fakhimi, G. Robinson reviewed)

1. STATEMENT OF THE PROBLEM

What are the mineralogical and chemical changes occurring within the hot zones and how will these changes affect the stability of the Questa rock piles? What are the reactions occurring in the hot zones? It is possible that weathering could be accelerated in these hot zones and result in weaker areas in the rock pile.

2. PREVIOUS WORK

Previous published work is summarized in McLemore et al. (2008b). The oxidation of pyrite is exothermic generating 11.7 MJ/kg (Lefebvre et al., 2002). The reaction can cause temperatures to rise above 65°C in places within some rock piles, allowing air convection to support pyrite oxidation (e.g. the Doyon mine in Canada; Lefebvre et al., 2001a, b, c). Wels et al. (2002, 2007) concluded that the key controls of oxygen transport into rock piles are diffusion, convection and barometric pumping. Morin et al. (1991) presents some case studies of gas flow through rock piles, including Rum Jungle, coal spoils in West Virginia, Mt. Washington, and Equity Silver mine. Many heap leach pads are specifically designed in attempt to increase the hot zones in order to facilitate more rapid and complete leaching.

3. TECHNICAL APPROACH

Existing data on the hot zones, including data collected by NMIMT (New Mexico Tech), were compiled and interpreted. Data sets available include (McLemore et al., 2008b):

- Characterization of samples from drill holes with hot zones
- Five-year data from RGC wells (Only data for 1st year was used in modeling, Lefebvre et al., 2001a,b,c, 2002; Robertson GeoConsultants Inc., 2000; Shaw et al., 2002; Wels et al., 2003, 2007)
- Temperature and gas data from drill holes in front rock piles
- Norwest temperature logs of front rock piles (Norwest Corporation, 2005)
- Temperature profiles of front rock piles by NMIMT (Reiter, in preparation)
- Thermal camera imaging of the surface of GHN and SGS rock piles (Shannon et al., 2005).

Samples were selected from drill cuttings of the hot zones in the Questa rocks piles for petrographic analyses (SOP 24), scanning electron microprobe (SOP 26), XRF whole-rock geochemistry (SOP 8), clay mineralogical analyses by X-ray diffraction (SOP 29), clay minerals stable isotope analysis (SOP 25; Graf, 2008), and slake durability tests (SOP 76).

4. CONCEPTUAL MODEL

Air flow through rock piles has the capacity to increase the rate of oxidation and weathering of pyrite by continuing the supply of oxygen and even water as humidity. According to Wels et al. (2003) and Dobchuk et al. (2004), oxygen transport occurs in rock piles by advection, convection, and diffusion in response to gas concentration, pressure and thermal gradients. These processes form cycles of evaporation and condensation inside the rock piles. As an effective source of oxygen, diffusion is probably restricted to the near surface of the rock piles at Questa (this is not necessarily true for all rock piles), but advection and convection have the potential to move air throughout the entire rock pile. The magnitude of air flow is controlled by complex interaction of the daily weather conditions and physical and chemical properties, including the stratigraphy and structure of individual layers of the rock piles. The first step in understanding the importance of air flow in rock piles is to identify, characterize, and field-monitor known conditions.

The hot zones represent areas within the rock pile where the heat builds up and does not disperse quickly; these zones at Questa appear to be localized within or near the base of the rock piles. Venting gases or water vapor have been observed from several sites at the Questa mine, mostly from drill holes in the front rock piles, a vent area on Sulphur Gulch South (SGS), and from cracks at the surface of Goathill North (GHN) prior to reclamation. Air flow was observed from coarse layers at GHN during examination of the trenches (McLemore et al., 2008a). Elevated temperatures and relative humidity explain these venting gases, locally called fumaroles, which are common at other mine sites (Morin et al., 1991; Ritchie, 2003; Wels et al., 2003). Recent experimental studies by Jerz (2002; Jerz and Rimstadt, 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 and producing hot zones within the rock piles. Norwest Corporation (2005) presents some evidence that hot zones could be restricted to the thicker rock piles, but visual observations indicate that venting of heat and gases occurred during the colder months at GHN and Capulin rock piles, which are thinner rock piles.

5. STATUS OF COMPONENT INVESTIGATION

Drill holes and vent areas are located in Figure 1. Mineralogy is in McLemore et al. (2008b).

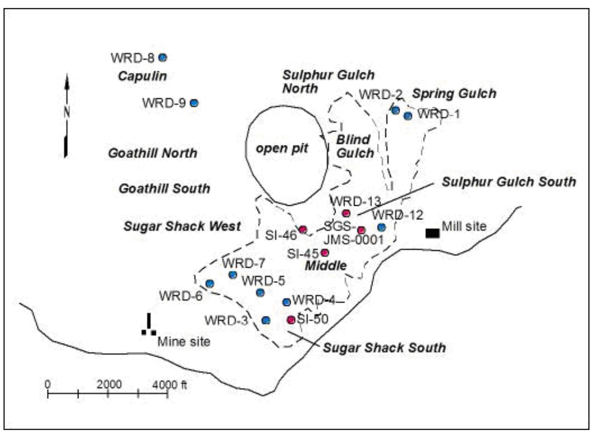
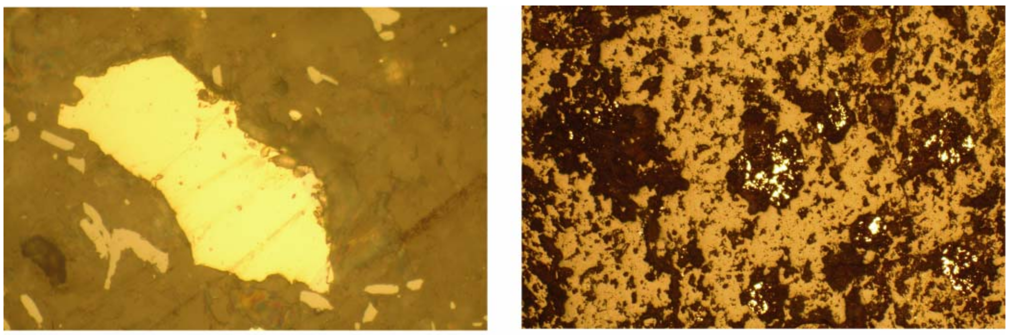


FIGURE 1. Locations of venting drill holes and a surface vent area. Blue circles indicate drill holes drilled in 1999 that contain monitoring instruments for temperature, O_2 and CO_2. Red circles indicate drill holes and a surface vent area (SGS-JMS-0001) that do not contain temperature and gas instrumentation.

Summary of Characterization

Petrographic observations used to describe oxidation include degree of pitting, changes in pyrite shape, iron staining or halos around the pyrite and overall appearance of the pyrite. Textures and discoloration typical of oxidation are observed near and in the hot zone. Pyrite grains from drill hole SI-50 display evidence of oxidation within the logged hot zone (Fig. 2). Pyrite varies with abundance with depth in the well; the highest concentrations are located in the hot zone (McLemore et al., 2008b). The concentration of calcite decreases in the hot zone, whereas the concentration of gypsum + jarosite and Fe oxides increases. The concentration of SO_4 increases and C decreases in the hot zone. The feldspar and clay mineral abundances do not change significantly in the hotter zones. In particular, kaolinite does not increase in relative abundance in the hot zones of the drill holes. There is no significant change in paste pH within the hot zones. Petrographic, mineralogic, and chemical characterization of hot zone samples is in McLemore et al. (2008b).



SSS-EHP-0004 29 -39 ft　　SSS-EHP-0026 239 -249 ft

FIGURE 2. Photomicrograph showing pyrite grains from drill hole SI-50 at 29-39 ft in depth (approximately 24ºC) and 239-249 ft in depth (approximately 52ºC) under plain polarized light using a petrographic microscope. Field of view is 1.8 mm.

Cementation appears to increase in the hot zone in SI-50 (Fig. 3). At the top of the hot zone in SI-50, there is little to no cementation and minor clay minerals (sample SSS-EHP-0017, depth 149-159 ft, approximately 55ºC). Deeper in the hot zone, cementation increased (sample SSS-EHP-0018, depth 159-169, approximately 63ºC). The cementation is a result of jarosite intergrown with clay minerals; Fe-oxide cementation is more prevalent below the hot zone (sample SSS-EHP-0032, depth 289-299 ft, approximately 30ºC). The concentration of calcite decreases with depth in the hot zone, whereas the concentration of gypsum + jarosite and Fe oxides increases with depth in the hot zone (McLemore et al., 2008b).

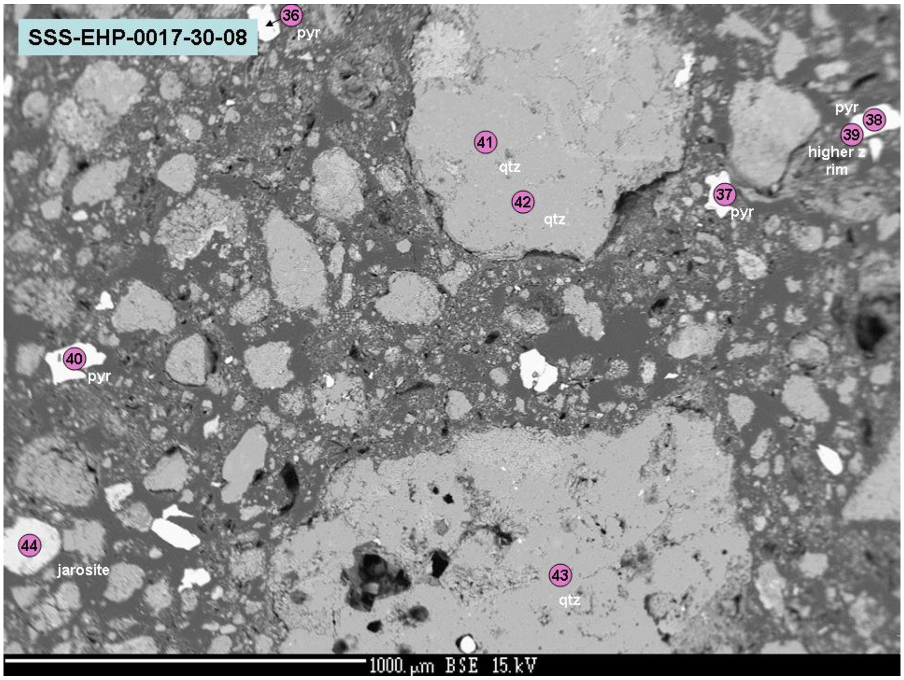


FIGURE 3. Backscattered image of sample SSS-EHP-0018-30-02 from the hot zone within SI-50 showing a close up of jarosite-cemented clast (depth 159-169 ft, approximately 60ºC).

Summary of Thermal Data from the Front Rock Piles

Shaw et al. (2002) described the results of one year of monitoring of temperature, CO_2, and O_2 from instrumented drill holes in the Questa rock piles (Fig. 1; Robertson GeoConsultants, 1999). CO_2 and temperature decreased with depth and O_2 increased with depth in the Robertson GeoConsultants (RGC) data. NMIMT obtained the data from these instrumented drill holes from 1999-2004 (McLemore et al., 2008b). Fourteen drill holes drilled in 2004 on the front rock piles are venting gases as well, but were not instrumented for temperature or gases (Norwest Corporation, 2005). The temperature ranges between 0° and 75°C, with the highest temperatures are in the thicker rock piles. There was no correlation between temperature and clay minerals or percentage of fines in the Norwest Corporation (2005) study or in the NMIMT study of SI-50 (McLemore et al., 2008b). Unfortunately, there is no temperature or gas concentration data from GHN. However, observed trends from instrumented holes in the front rock piles and Capulin rock pile can be used as analogs to understand air and water vapor flow in GHN.

Oxygen concentrations were lower, but CO_2 concentrations were considerably higher than ambient air values in the hot spots. Concentrations of O_2 and CO_2 had a negative correlation that manifested themselves in both the depth profiles (Fig. 4) and time plots (McLemore et al., 2008b). The highest O_2 and lowest CO_2 concentrations occurred during the colder months. Temperatures varied with the seasons at depths less than 20 to 30 ft. At depths deeper than 30 ft depths, temperatures did not show seasonal variations, but rather decreased slightly over the five-year period with a maximum decrease of approximately -12°C. Over the same period, mean O_2 concentrations increased by up to 10% and mean CO_2 concentrations decreased by up to 1%. Three of the rock piles (Spring Gulch, Sugar Shack South and Sugar Shack West) had higher average temperatures and lower O_2 concentrations in boreholes at higher elevations. Two rock piles (Spring Gulch and Sugar Shack South) showed higher CO_2 concentrations at higher elevations.

These interpretations suggest that ample air enters the rock piles through the toe and flows upward through rubble zones and other coarse layers by convection to higher elevations (Wels et. al., 2003). Cool air flows through many of the coarse gravel-cobble zones within the interior units of GHN, as observed during the sampling and mapping of the trenches. There are minor air entry and exit points along the slopes of the rock piles. This phenomenon is observed along the road in SGS rock pile, where warm air exits the pile along the slope. However, the mass flow of air from the toe to the top of the piles is the dominant flow mechanism. Oxygen is used up from the air by oxidation processes, mostly pyrite oxidation catalyzed by micro-organisms, and CO_2 is produced by decomposition of carbonates. Pyrite oxidation is strongly exothermic and produces the heat that controls the temperature of the piles at depth (Shaw et. al., 2002). The chemical processes are slowing down with time due to reduction of reactants and/or coating of mineral surfaces by reaction products, resulting in decreasing temperatures, decreasing CO_2 concentrations, and increasing O_2 concentrations; in other words, the rock pile material is approaching chemical equilibrium. The flow of air into the rock pile is controlled in part by the difference in temperature between ambient air and the interior of the rock pile and, therefore, there is greater influx of air during the colder months (Wels et. al., 2003). This accounts for the seasonal variation of O_2 and CO_2 concentrations even at depths where temperature does not change with the seasons. Table 1 shows the elevation and mean values of temperature, O_2 and CO_2 for each borehole in the four monitored piles.

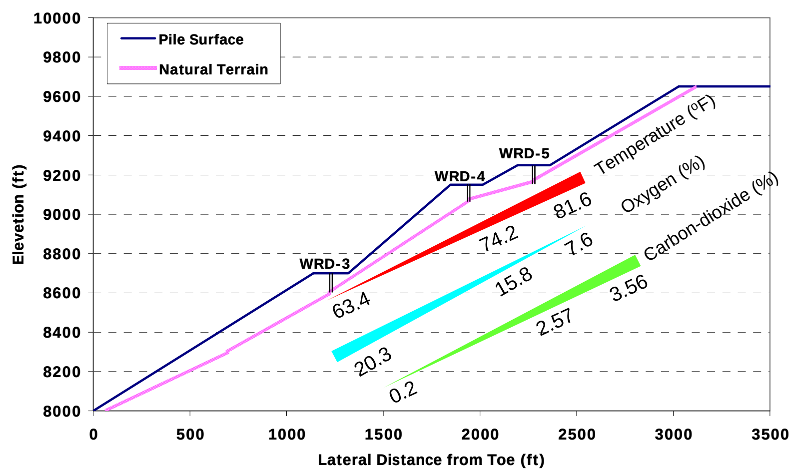


FIGURE 4. Section through monitored drill holes in Sugar Shack South showing the relationship between O_2, CO_2, and temperature within the rock pile. The thicker line indicates increase in the parameter.

TABLE 1. Calculated mean values by drill hole.

Rock Pile	Drill Hole Number	Elevation (ft)	Temperature ºC	Oxygen (%)	Carbon Dioxide (%)
Spring Gulch	WRD-1	9100	10.4	20.00	0.33
	WRD-2	9250	21.9	12.23	0.52
Sugar Shack South	WRD-3	8700	17.4	20.32	0.20
	WRD-4	9150	23.4	15.83	0.80

Rock Pile	Drill Hole Number	Elevation (ft)	Temperature ºC	Oxygen (%)	Carbon Dioxide (%)
	WRD-5	9250	27.6	7.60	2.57
Sugar Shack West	WRD-6	9000	12.9	10.20	3.56
	WRD-7	9400	16.9	5.46	2.40
Capulin	WRD-8	9810	18.9	18.50	0.24
	WRD-9	9800	15.7	17.77	0.20

Summary of Thermal Camera Imagery

Thermal camera surveys were conducted on two of the nine rock piles, SGS and GHN (Shannon et al., 2005). The SGS rock pile was selected because of an identified heat vent located on the slope below the bench where hole WRD-13 was drilled that was venting steam, presumably as a result of pyrite oxidation at depth. The stable and unstable portions of the GHN rock pile were investigated to attempt to detect evidence of heat vents or thermal anomalies caused by variations in moisture content or gas entering or exiting the rock pile, but none were found. Thermal imaging of the SGS rock pile revealed a heat vent of roughly 40 m by 30 m that had the same maximum temperature of 18°C during February and May 2004. Maximum temperature in this area was much larger than the ambient temperature in February (0-2° C) and May (4-6° C). During the February survey, the heat vent had little to no snow cover, and the rock-pile material was very wet. More details are in Shannon et al. (2005).

Summary of Gas Analyses

A portable RKI Eagle gas analyzer was used to determine the composition of the venting gases and monitor the changes in gas composition of these sites, especially at the surface vent area with time. Gases from five drill holes and one surface vent area on the front rock pile were analyzed (McLemore et al., 2008b). Locations of these drill holes are in Figure 1. SGS-JMS-0001 is the surface vent area on SGS rock pile that the team began observing in March 2004 (Fig. 5). Gas measurements were obtained at various depths up to 90 ft using a plastic tube that was lowered into the holes to collect gases at depth and transmit them to the instrument. Gas analyses are in Appendix 1. More details are in McLemore et al. (2008b).

FIGURE 5. Steam venting from fractures in Sulphur Gulch South (SGS-JMS-0001) vent area, during a snow storm. The soil temperature is typically >4ºC and snow melts as soon as it hits ground.

Summary of temperature logs

Subsurface temperature data (T logs) were taken at 18 drill holes on the four front rock piles at the Questa mine (Norwest Corporation, 2005; Reiter, in preparation), and the drill cuttings were described. From these descriptions and measured temperatures, it appears that the most intense thermal source (pyrite oxidation) typically occurs over an interval that is a small fraction of the drill-hole depth. Because the rock piles are unsaturated (liquid water is not encountered in rock-pile material within the drill holes) and vapor is observed venting from the ground surface at some locations, much of the fluid flux is vapor. Gas analyses confirm this. The T logs help to define the depths of pyrite oxidation, while the character of the T logs suggests mechanisms for the heat transferring processes. Hot zones do appear to correspond to zones of red and yellow coloring and high concentrations of pyrite (McLemore et al., 2008b; Reiter, in preparation).

Summary of Stable Isotopic Analyses

Eight samples of mixed clay minerals were collected from 2 drill holes and prepared in the same way as the GHN and scar clay samples. Isotopically, seven of the eight samples are very similar to the GHN samples (Fig. 6). Because of the overlap in compositions with GHN, the most likely interpretation is that they have a hydrothermal origin similar to the GHN clays. However, because of the higher temperature in the hot zones, authigenic clays will begin to approach the compositions of hydrothermal clays. We feel it is unlikely that these clays were formed in the piles in response to higher temperature (70°C) weathering but is not as clear cut as the origins of clays in GHN. The hot zone samples were analyzed in the same way as the rest of the clays mineral samples. All of the samples have the potential to be contaminated with some interlayer water from the clay minerals. Due to mass balance and sample preparation considerations this would have a greater effect on the δD than on the δ^{18}O. Despite the potential contamination with recent waters δ^{18}O values still argue for a hydrothermal origin for the clays.

One sample SSS-EHP-0017 is from the drill cuttings interval SI-50 149-159 ft, and has a heavier hydrogen and oxygen isotopic compositions than the other samples from this hole. In the drill cuttings, the interval from 139-169 ft is much different from the intervals above and below this interval. From 139-169 ft there is a pronounced increase in fine-grained material, where there is a bimodal assemblage of gravel-sized rock fragments in a fine-grained matrix, as compared to other samples from the drill cuttings where gravel-sized rock fragments are supported by smaller fragments. Although rock fragments have similar angularity throughout the cuttings, this interval is much lighter in color (yellowish-tan) than the rest of the cuttings (light to dark grey). This could be evidence of increased hydrothermal alteration and mineral alteration; relatively unaltered pyrite is found within the sample from the 149-159 ft cuttings interval in question. Theories for this heavy isotopic sample could be that this interval formed in the hot zone from evaporated water, or that the high clay content in this interval acted as an isotopic sink and the clays preferentially used the heavier isotopes for structural water and hydrous interlayers. This sample is enigmatic. Not only is it isotopically heavier, but it also was more difficult to analyze. By itself it does not prove that any different weathering process are occurring in the hot zone, but suggests that additional work is needed to see if other similar samples can be found. This outlier, however it formed, shows more work is required to better understand the dynamics of fluid flow through debris flows at the Questa mine site.

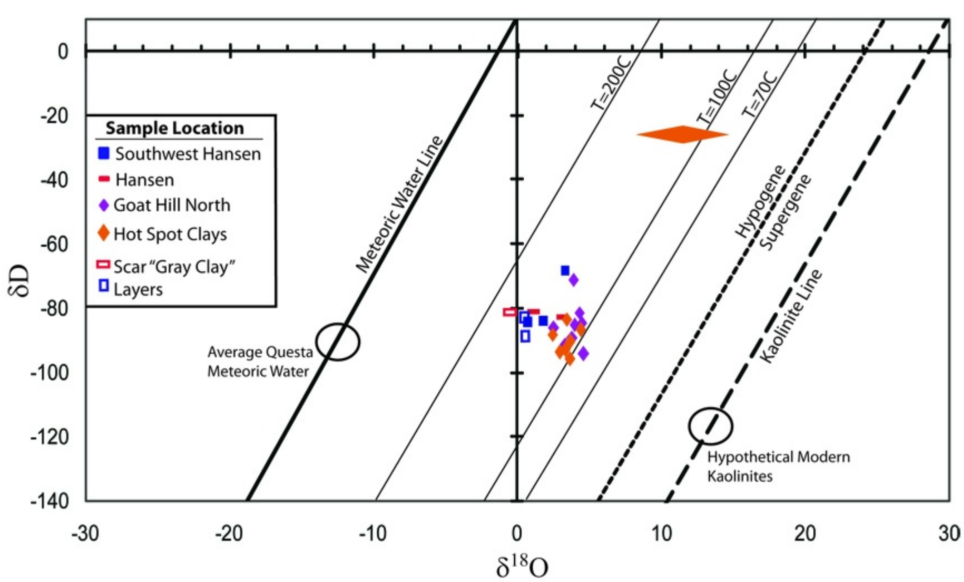


FIGURE 6. Hydrogen and oxygen isotope analyses of hot zone clays. All but one of the hot zone clays plot with the GHN clays. That sample has a considerably heavier composition. δD values may have been affected by interlayer water.

Slake durability test

Slake durability tests are a measure of the strength of rock fragments. The slake durability measurements of rock-pile material collected from the hot zones (Fig. 7) are similar to the measurements obtained for other materials in the Questa area (DRA-46; Ayakwah et al., 2009) and indicate high durability. These measurements along with the similarity in mineralogy and chemistry, especially considering that no new clays are being formed by weathering of the material in the hot zones, suggests that the hot zones have not caused noticeable changes in the durability of rock fragments so far.

Sample SSS-EHP-0023 (SI 50 209-219) was an outlier in the hot zone sample suite and not plotted on Figure 6; it had a slake durability index of 39%. It was not a rock fragment, but a cemented "conglomerate". The color of this sample is yellow to tan before rinsing and gray to white to brown after rinsing. Rock fragments from this sample ranged in size from coarse-grained sand to cobble-sized, the fragments are sub-rounded to sub-angular, and are primarily andesite and rhyolite (Amalia Tuff). There are few, if any, Fe oxide rims along any of the rock fragments. There were no visible pyrite, gypsum, or jarosite crystals in the soil matrix. This sample compares to others from the same drill cuttings by having more small rock fragments and by having less cementing material. The sample of drill cuttings just below this interval (219-229 ft) is highly altered with a higher clay content and is well cemented; rock fragments from other sampling intervals of this drill cuttings also are much more angular.

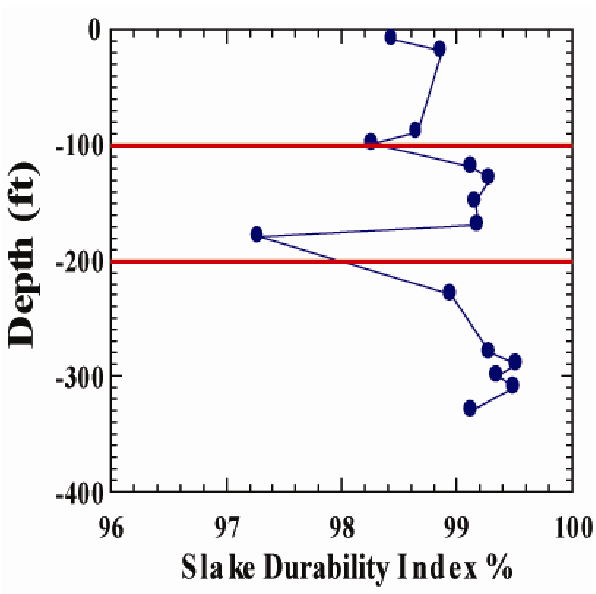


FIGURE 7. Variations in slake durability index with depth in drill hole SI-50. Temperature log is in Ayakwah et al. (2009). Red lines indicate approximate boundaries of the hot zone (i.e. where temperatures exceed 50ºC).

6. RELIABILITY ANALYSIS

Rock piles are open systems with respect to the vapor, air, and heat flow and transport (Morin et al., 1991; Reiter, in preparation). A convective system could be transferring heat from one location in the pile to another, resulting in a measured heat source that cannot be identified, i.e. high temperature, but no signs of pyrite oxidation. The hot zones themselves are difficult to sample and map. The only samples we have collected are from the drill cuttings through the hot zones logged by Norwest Corporation (2005), NMIMT (McLemore et al., 2008b; Reiter, in preparation) and from the surface of the vent at SGS. Direct shear tests can not be conducted reliably on drill cuttings; instead slake durability tests were conducted on rock fragments. Only one drill hole was analyzed in detail; other hot zones also should be analyzed.

The Questa rock piles are heterogeneous with respect to mineralogy, lithology, particle size, and moisture content. The techniques used for this study are not able to detect small differences in the abundances of clay minerals or minor changes in the mineral chemistry. The methods using pre-treating the clay-sized stable isotope samples can not remove clay-sized silicate minerals such as quartz (Graf, 2008). The limited sampling conducted in the hot zones does not allow for any confidence to be placed on the one isotopically outlier found.

Samples collected are complete, comparable, and representative of the defined population at the defined scale for the drill hole selected. Precision and accuracy are measured differently for each field and laboratory analysis (parameter), and is explained in the project reports, SOPs, DRAs, and described in more detail in McLemore and Frey (2008). Most laboratory analyses depend upon certified reference standards and duplicate and triplicate analyses as defined in the project SOPs.

Some of the technical and data uncertainties 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.
- The GHN rock-pile materials are a mixture of different lithologies and hydrothermal alteration mineral assemblages, 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.
- The pre-treatment methods used for the clay-sized stable isotope samples are not able to remove clay-sized silicate minerals such as quartz. However, the presence of other silicate minerals was verified using the post-treatment XRD patterns. The samples for isotope analysis were not dried at high temperature and thus not all the interlayer water may have been removed from the sample. This could have a big effect on the δD values determined but not much effect on the $\delta^{18}O$. Despite the uncertainty in δD, the oxygen values still suggest that the clays were not in equilibrium with local water and thus not newly formed.

7. CONCLUSIONS OF THE COMPONENT

- Hot zones are found in the Questa rock piles; the temperature ranges between 0° and 75°C. Oxygen concentrations were lower, but CO_2 concentrations were considerably higher than ambient air values. The CO_2 is likely from dissolution of calcite. The data suggest that ample air enters the rock piles through the toe and flows upward through rubble zones and other coarse layers by convection to higher elevations (Wels et. al., 2003).
- The Questa rock piles, including the hot zones, are heterogeneous with respect to mineralogy, lithology, particle size, and moisture content (McLemore et al., 2008b). Weathering in the hot zones is typical of weathering found elsewhere in the Questa rock piles and analog sites. The dissolution of pyrite, calcite, and to a lesser extent chlorite, illite, and other silicate minerals are the more important chemical reactions that result 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.

- The clay mineral abundances do not change significantly in the hot zones. In particular, kaolinite does not significantly increase in relative abundance in the hot zones of the drill holes.
- Stable isotope analysis of clay minerals supports the interpretation that no new weathering clays are generated in the hot zones.
- The slake durability measurements of rock-pile material collected from the hot zones are similar to the measurements obtained for other materials in the Questa area (DRA-46; Ayakwah et al., 2009) and indicate high durability. These measurements along with the similarity in mineralogy and chemistry, especially considering that no new clays are being formed by weathering of the material in the hot zones, suggests that the hot zones so far have not noticeably changed in slake durability as a result of weathering.
- Since the samples collected from the hot zone show 1) no increase in clay minerals, 2) increased cementation and 3) the rock fragments show a high durability, it is likely that these zones are similar to areas sampled within the rock piles that show high friction angle (DRA 42) and have no effect on slope stability. However, direct shear tests could not be performed on the material collected from drill cuttings. Therefore, it is still uncertain as to the effect hot zones have on slope stability.

8. REFERENCES CITED

Ayakwah, G.F., McLemore, V.T., Fakhimi, A., and Viterbo, V.C., 2009, Effects of weathering and alteration on point load and slake durability indices of the Questa rock piles, New Mexico: SME Annual Meeting, Preprint, Denver, Colorado.

Dobchuk, B.S., Barbour, S.L., MASCE, and Zhou, J., 2004, Prediction of water vapor movement through waste rock: Journal of Geotechnical and Geoenvironmental Engineering, March, p. 293-302.

Graf, G.J., 2008, Mineralogical and geochemical changes associated with sulfide and silicate weathering, natural alteration scars, Taos County, New Mexico: M. S. thesis, New Mexico Institute of Mining and Technology, Socorro.

Jerz, J.K., 2002, Geochemical reactions in unsaturated mine wastes: PhD. Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Jerz, J.K. and Rimstidt, J.D., 2004, Pyrite oxidation in humid air: Geochimica Cosmochimica Acta, v. 68, p. 701-714.

Lefebvre, R., Hockley, D., Smolensky, J., and Gélinas, P., 2001a, Multiphase transfer processes in waste rock piles producing acid mine drainage 1: Conceptual model and system characterization: Journal of Contaminant Hydrology, v. 52, p. 137-164.

Lefebvre, R., Hockley, D., Smolensky, J., and Lamontagne, A., 2001b, Multiphase transfer processes in waste rock piles producing acid mine drainage 2: Applications of numerical simulation: Journal of Contaminant Hydrology, v. 52, p. 165-186.

Lefebvre, R., Lamontagne, A., and Wels, C., 2001c, Numerical simulations of acid drainage in the Sugar Shack South rock pile, Questa Mine, New Mexico, USA, *in* Proceedings 2nd Joint IAH-CNC and CGS Groundwater Specialty Conference, 54th Canadian Geotechnical Conference September 2001: Calgary, Alberta, Canada.

Lefebvre, R., Lamontagne, A., Wels, C. and Robertson, A.M., 2002, ARD Production and Water Vapor Transport at the Questa Mine, *in* Proceedings Ninth International Conference on Tailings and Mine Waste, Tailings and Mine Waste ‘02: A.A. Balkema Publishers, Lisse p. 479-488.

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., 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 Chevron, 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.T., Tachie-Menson, S., Sweeney, D., Donahue, K., Dickens, A., Dunbar, N., Heizler, L., and Campbell, A., 2008b, Characterization of hot zones in the Questa rock piles: unpublished report to Chevron, Task B1.3.2.

Morin, K.A., Gerencher, E., Jones, C.E., and Konasewich, D.E., 1991, Critical review of acid drainage from waste rock: MEND report 1.11.1, 193 p.

Morth, A.H. and Smith, E.E., 1966, Kinetics of the sulfide-to-sulfate reaction: Am. Chem. Soc. Div. Fuel Chem. Preprints no. 10, 83 p.

Norwest Corporation, 2005, Questa Roadside Rockpiles: 2005 Operational Geotechnical Stability Evaluation: Molycorp report, 107 p.

Reiter, M., in preparation, Fluid flow and the geothermal regime in the Roadside rock piles at the Chevron Mining Inc. molybdenum mine, Questa, New Mexico: publication in review.

Ritchie, A.I.M., 2003, Oxidation and gas transport in piles of sulfidic material. *in* ed Jambor, J.L., Blowes, D.W., Ritchie, A.I.M., Environmental aspects of mine wastes: Short course series 31, Mineralogical Association of Canada, Ottawa, ON, Canada, p. 73-94.

Robertson GeoConsultants, Inc., 1999, Interim Report: Questa Waste Rock Pile Drilling, Instrumentation and Characterization Study, Open-file Report No. 052007/1 for Molycorp Inc.

Robertson GeoConsultants, Inc., 2000, Progress Report: Questa Mine Rock Pile Monitoring and Characterization Study, Open-file Report No. 052007/3 for Molycorp Inc.

Shannon, H., Sigda, J., van Dam, R., Hendrickx, J., and McLemore, V.T., 2005, Thermal camera imaging of rock piles at the Questa Molybdenum Mine, Questa, New Mexico: National Meeting of the American Society of Mining and Reclamation, Breckenridge, Colo, June, CD-ROM, http://geoinfo.nmt.edu/staff/mclemore/Molycorppapers.htm, accessed December 06, 2007.

Shaw, S., Wels, C., Robertson, A., and Lorinczi, G., 2002, Physical and geochemical characterization of mine rock piles at the Quest Mine, New Mexico: An overview, *in* Proceedings Ninth International Conference on Tailings and Mine Waste, Tailings and Mine Waste '02: AA Balkema Publishers, Lisse, p. 447-458.

Wels, C., Lefebvre, R., and Robertson, A.M., 2003, An overview of prediction and control of air flow in gas acid-generating waste rock dumps; in ICARD 2003—Proceedings from the 5th international conference on acid rock drainage: The Australasian Institute of Mining and Metallurgy, Melbourne, p. 639-650.

Wels, C., Loudon, S., and Fortin, S., 2002, Factors influencing net infiltration into mine rock piles at Questa Mine, New Mexico; *in* Tailings and Mine Waste '02: proceedings of the Ninth International Conference on Tailings and Mine Waste: Fort Collins, Colorado, USA, 27-30 January, p. 469-477, also at http://www.robertsongeoconsultants.com/papers/welfin.pdf, accessed December 06, 2007.

Wels, C. Lefebvre, R., and Robertson, A.M., 2007, Control of air flow in waste rock dumps: Infomine E-book, 30 p.

9. TECHNICAL APPENDICES

Shannon, H., Sigda, J., van Dam, R., Hendrickx, J., and McLemore, V.T., 2005, Thermal camera imaging of rock piles at the Questa Molybdenum Mine, Questa, New Mexico: National Meeting of the American Society of Mining and Reclamation, Breckenridge, Colo, June, CD-ROM, http://geoinfo.nmt.edu/staff/mclemore/Molycorppapers.htm, accessed December 06, 2007.

McLemore, V.T., Tachie-Menson, S., Sweeney, D., Donahue, K., Dickens, A., Dunbar, N., Heizler, L., and Campbell, A., 2008, Characterization of hot zones in the Questa rock piles: unpublished report to Chevron, Task B1.3.2

APPENDIX 1. Gas analyses in volume percent. A "0" indicates that the measurement is below detection limit. SGS-JMS-0001 is located along the main road on Sulfur Gulch South at UTM 455225 W, 4061445 N, zone 13. Soil temperature was measured by soil thermometer. Humidity and temperature of vapor were measured by Kestrel instrument at the drill hole collar.

Station number	Sample number	Drill hole number	Date	time	O_2	CO
SGS-JMS-0001	SGS-PXW-0007		2/22/2005	14:46	20.9	0
SGS-JMS-0001	SGS-SAW-0001		4/10/2005	9:00	20.9	0
SGS-JMS-0001	SGS-STM-0001		5/6/2005	8:45	20.9	0
SGS-JMS-0001	SGS-STM-0002		5/6/2005	9:00	20.9	0
SGS-JMS-0001	SGS-STM-0003		5/6/2005	9:13	19.4	0
SGS-JMS-0001			6/16/2005	1:20	20.1	0
SGS-JMS-0001	SGS-ESO-0001		6/16/2005	1:15	20.9	0
SGS-JMS-0001			9/20/2005		19.1	0
SGS-SAW-0003	SGS-SAW-0003		4/10/2005	9:15	19.2	0
SI-44		SI-44	5/6/2005	9:52	9.8	0
SI-45		SI-45	2/22/2005		3.5	0
SI-45		SI-45	4/7/2005	13:27	2.9	0
SI-45		SI-45	5/6/2005	10:25	1.4	0
SI-45		SI-45	9/20/2005		12.1	0
SI-46		SI-46	2/22/2005	9:30	5.9	13
SI-46		SI-46	2/22/2005	15:23	5.4	12
SI-46		SI-46	2/22/2005	15:30	5.4	16
SI-46		SI-46	4/7/2005	13:08	5	15
SI-46		SI-46	4/10/2005	9:52	5.1	16
SI-46		SI-46	5/6/2005	10:05	2.9	15
SI-46		SI-46	6/16/2005	2:46	18.7	0
SI-46		SI-46	9/20/2005		7.7	4
SI-50		SI-50	2/22/2005	10:40	11	0
SI-50		SI-50	4/7/2005	14:19	17.4	0
SI-50		SI-50	5/6/2005	12:44	18.8	0

Station number	Sample number	Drill hole number	Date	time	O_2	CO
SI-50		SI-50	6/16/2005	12:57	17.4	0
WRD-13		WRD-13	2/22/2005	13:59	20.9	0
WRD-13		WRD-13	2/22/2005	13:16	19.9	0
WRD-13		WRD-13	2/22/2005	13:25	20	0
WRD-13		WRD-13	2/22/2005	13:52	20.4	0
WRD-13		WRD-13	2/22/2005	13:10	20	0
WRD-13		WRD-13	2/22/2005	13:43	20	0
WRD-13		WRD-13	2/22/2005	9:50	20.9	0
WRD-13		WRD-13	2/22/2005	13:30	20	0
WRD-13		WRD-13	4/7/2005	12:52	20.3	0
WRD-13		WRD-13	4/10/2005	8:42	19.4	0
WRD-13	SGS-STM-0005	WRD-13	5/6/2005	9:38	19.4	0
WRD-13		WRD-13	6/16/2005	1:40	20.1	0
WRD-13		WRD-13	9/20/2005		20.5	0
WRD-3		WRD-3	5/6/2005	12:40	20.9	0
WRD-4		WRD-4	2/22/2005	10:20	19.3	0
WRD-4		WRD-4	4/7/2005	13:35	18.7	0
WRD-4		WRD-4	5/6/2005	10:15	18.5	0
WRD-4		WRD-4	9/20/2005		19.2	0

Station number	CO_2	SO_2	H_2S	Temperature ºC	Humidity %	Comments
SGS-JMS-0001	0.16	0	0	25	89.5	tube in soil cracks at spot where steam was venting, sulfur smell
SGS-JMS-0001	0.2	0	0	17		soil temp
SGS-JMS-0001	0.24	0.3	0	16		upper site
SGS-JMS-0001	0.18	0.3	0	20		upper site, moss
SGS-JMS-0001	0.6	0.4	0	23		south of precipitation collector
SGS-JMS-0001	0.3	0	0			
SGS-JMS-0001	0.04	0.1	0			
SGS-JMS-0001		0	0			
SGS-SAW-0003	0.78	0	0	25		soil temp
SI-44	1.2	0.3	0	24	100	warm, moist
SI-45	5	0	0			well was capped, bag over well during measurement
SI-45	5	0	0	16	75	with bag
SI-45	4.12	0	0	18	50	
SI-45		0	0	27	50	
SI-46	1.7	0.35	0	70		with bag over well to prevent mixing with atmosphere, water condensation in bag
SI-46	1.88	0.3	0	69	100	with bag
SI-46	1.9	0.4	0			with bag

Station number	CO_2	SO_2	H_2S	Temperature ºC	Humidity %	Comments
SI-46	1.9	0.7	0	70.8	100	with bag
SI-46	1.7	0.9	0	72	100	with bag
SI-46	1.38	0.6	0.5	70	100	steam venting
SI-46	0.2	0.2	0			
SI-46		0	0	70.1	100	
SI-50	1.18	0	0			with bag
SI-50	0.58	0.1	0	25.7	10.1	with bag
SI-50	0.48	0	0	17	34	
SI-50	0.7	0.3	0			
WRD-13	0.32	0	0		89.5	with bucket
WRD-13	0.26	0	0			with bucket
WRD-13	0.34	0	0			with bucket
WRD-13	0.36	0	0			with bucket
WRD-13	0.22	0	0			with bucket
WRD-13	0.38	0	0			with bucket
WRD-13	0.38	0	0			left bucket over well while measuring gas
WRD-13	0.34	0	0			with bucket
WRD-13	0.38	0	0	38		
WRD-13	0.56	0	0	10	100	steaming, snowing
WRD-13	0.38	0	0	24	73	steam venting, S smell, humidity 73%, temp 23C
WRD-13	0.23	0.2	0			
WRD-13		0	0	27	100	
WRD-3	0.06	0	0	16	22	
WRD-4	0.56	0	0			well covered by barrel
WRD-4	0.54	0	0	20.9	65	with bag
WRD-4	0.46	0	0	22	39	
WRD-4		0	0	27.8	34	