

**DRA-27a. CEMENTATION IN THE QUESTA ROCK PILES**

V.T. McLemore, December 20, 2008, revised December 31, 2008 (reviewed by A. Campbell)

**1. STATEMENT OF THE PROBLEM**

Can cementation of rock-pile material be documented? What minerals form the cement? Cementation is one part of cohesion, which is an important component of shear strength (DRA-47). This DRA summarizes the cementation of the Questa rock piles.

**2. PREVIOUS WORK**

*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 (modified from Neuendorf et al., 2005). *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 can occur at the transition between oxidized and reduced zones and saturated and unsaturated zones in the rock piles (Graupner et al., 2007). 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). Hardpans are zones at the capillary fringes where agglutination of particles results from capillary transport within an oxygen-dominated environment (Graupner et al., 2007). Continuous hardpan layers were not observed in the Questa rock piles.

Studies of the formation of crusts, hardpans, cemented layers, and duricrusts within tailings piles, where saturated conditions exist, are common in the literature (Blowes et al., 1991; Dill et al., 2002; Graupner et al., 2007), but not many studies of cementation within rock piles have been reported. Blowes et al. (1991) described two different chemical systems cementing sulfide-rich tailings; 1) gypsum and melanterite and 2) Fe (III) minerals (goethite, lepidocrocite, ferrihydrite, and jarosite). Dill et al. (2002) found that the resulting mineral assemblage in tailings piles from the Matchless pyrite-Cu mine were determined by the amount and type of ore and gangue minerals present as well as the chemical reagents used in the processing of the ore. They defined the cementation process according to the predominant mineralogy as sulfide oxidation and sulfate precipitation, phosphatization, carbonatization, and chloritization. Graupner et al. (2007) found that mineral dissolution, precipitation, transformation, and mass transport were related to the formation of hardpan and cemented layers with the Freiberg tailings and that this cementation resulted in a restriction of downward movement of the oxidation front and a reduction of the extent of erosion. They concluded that the potential of tailings to form cemented layers and hardpans was increased by a heterogeneous

distribution of grain sizes, low permeability, and presence of reactive minerals in the upper most layers. McGregor and Blowes (2002) examined three cemented layers within three tailings and found that, although all three layers differed in mineralogy, chemistry, and morphology, all three layers evolved with time from gypsum-jarosite based cement to goethite-rich cement.

Cementation or precipitation of minerals during heap leaching or solution mining is a potential problem that could prevent full recovery of the economic metal. Several studies have examined this problem. Canterford et al. (1985) found that gypsum and jarosite were the predominant minerals that precipitated during the acid-solution mining of copper ores.

### **3. TECHNICAL APPROACH**

The technical approach to identifying and understanding cementation of the rock piles involved a combination of 1) field observations (SOP 5), 2) petrography (described in SOP 24), 3) electron microprobe analyses on samples to determine the morphology and nature of the cement, mineral phases present, chemistry of the cement minerals, and to examine textural relationships of the cement, and 4) in-situ shear testing. Samples examined include the 1) rock-pile material, 2) rock-pile material from the hot zones, 3) natural analogs, 4) samples from the in-situ testing and 5) observations from humidity cells samples.

The cementation of each sample was visually described in the field as none, poor (some rock fragments were cemented together, which could be broken apart by hand), moderate (many rock fragments were cemented together, which had to be separated using a rock hammer or other tool) and well cemented (many rock fragments were cemented together, which had to be separated by force by a rock hammer). Cementation was further estimated and described during the petrographic analyses using the same definitions as in the field. The cementing minerals were identified by hand lens in the field and then confirmed by petrographic analyses using a binocular microscope in the laboratory, followed by electron microprobe analysis on selected samples.

Details of sample collection and analysis are in the project SOPs and summarized in DRA-0. The collected samples from the rock piles consisted of a heterogamous mixture of rock fragments ranging in size from boulders (0.5 m) to <1 mm in diameter within a fine-grained soil matrix. During the probe analysis, both rock fragments and soil matrix of each sample were examined. Field photos of each sample are in McLemore et al. (2008a, b), project reports, and the project data repository.

Cementation is one part of cohesion, which is composed of three components; 1) interlocking of particles, 2) cementation, and 3) matric suction. An in-situ shear test apparatus was designed at New Mexico Tech and fabricated by Questa mine engineers to measure the cohesion of the Questa materials (Fakhimi et al., 2008). In-situ tests were performed on both rock piles and natural weathering analogs (DRA-47; Boakye, 2008). Areas of alteration scars, weathered bedrock, and debris flows near the Questa mine have been identified as natural weathering analogs to the mineralogical changes in the rock piles expected during long-term weathering (DRA-47a; Ludington et al., 2005; McLemore, 2008b; McLemore et al., 2008c; Campbell and Lueth, 2008; Graf, 2008). Note that the weathering processes operating in the natural analogs share many

similarities to those in the rock piles, although certain aspects of the physical and chemical systems are different (DRA-19, 20, 22).

#### 4. CONCEPTUAL MODEL(S)

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 react with minerals in and at the surface of the rock pile. The pore fluids can precipitate minerals to form cement that binds rock fragments and soil matrix together.

The Questa rock piles were formed by end-haul dumping that results in 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 (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. Cementation at the formation of the rock piles was zero, so any cementation documented in the rock piles is the result of weathering (or diagenesis).

The decrease in grain size that results predominantly from physical weathering, results in increased surface area, which leads to greater chemical reactivity and exposure of fresh mineral surfaces and also releases pre-mining hydrothermal clay minerals from the mined material, which can then act as cement in the rock pile. Physical weathering was probably most prominent during end-dumping to form the rock piles than it will be in the future. Future physical weathering will be focused at the surface of the rock piles (due to freeze/thaw and thermal contraction/expansion). 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; Campbell and Lueth, 2008). Crystallization of mineral phases also can break up the rock, for example the crystallization of salt increases the volume by as much as 5%.

To obtain the cohesion parameters for the same values of matric suction, the modified Mohr-Coulomb failure criterion (Eqs. 1a to 1c) was used (Fredlund and Rahardjo, 1993)

$$\tau = c + (\sigma - u_a)\tan\phi \quad (1a)$$

$$c' = c - (u_a - u_w)\tan\phi^b \quad (1b)$$

$$c'' = c' + (u_a - u_w)\tan\phi^b \quad (1c)$$

where  $\tau$  and  $\sigma$  are shear and normal stresses,  $u_a$  and  $u_w$  are air and pore water pressures,  $c$  and  $\phi$  are cohesion and friction angle, and  $\phi^b$  is the angle that dictates the increase in cohesion due to the increase in matric suction,  $(u_a - u_w)$ . With  $u_a$  equal to zero, an assumed  $\phi^b$  of 15° (Fredlund and Rahardjo, 1993), the cohesion  $c$  in Eq. (1b) can be used to find the cohesion  $c'$  for zero suction. Eq. 1c is then can be used to obtain the cohesion corresponding to a given matric suction ( $c''$ ).

## 5. STATUS OF COMPONENT INVESTIGATION

### Cementation in rock piles

Cementation in the rock piles varies from none to moderate, with local discontinuous, well-cemented layers (Access database; McLemore et al., 2008a). Authigenic gypsum, jarosite, soluble efflorescent salts, Fe-oxide minerals and clay minerals liberated from the mined rock material during construction of the rock piles (i.e. pre-mining hydrothermal clay minerals), have cemented parts of the Questa rock-pile material. Not all of the rock-pile material is cemented. In the short term, cementation at the surface is controlled by jarosite, gypsum and soluble efflorescent salts. The repeated wetting and drying cycle (infiltration, drainage, evaporation, and oxidation) is the major influence on precipitation and dissolution of these soluble minerals (Nordstrom et al., 1979; Nordstrom, 1982; Perkins et al., 1995). These minerals form a thin, hard crust at the surface of the rock piles, which can be partially or completely dissolved during wet periods (DRA-8; Geise et al., 2008). During infiltration into the rock piles, these soluble minerals are dissolved and carried farther into the rock pile and re-precipitated, in some cases precipitated as less soluble Fe oxide minerals (Perkins et al. 1995). The less stable minerals could form the building blocks for longer-term cementation consisting of Fe oxides, such as hematite and goethite, and amorphous Fe and Mn material (Delvigne, 1998; McGregor and Blowes, 2002).

Electron microprobe analysis of rock-pile material shows cementation by Fe-oxide minerals and gypsum. The Fe-oxide cement consists of a fine veining network of Fe-oxide intergrown with the clay in the soil matrix (Figs. 1-4). Although the cementation that is observed in the rock-pile material is in close association with rock fragments, it is not typically observed in the rock fragments themselves. Gypsum is observed in a number of rock-pile samples as a cement, and typically occurs as individual bladed crystals (Figs. 5, 6).

Ferricretes are accumulations of secondary Fe-oxyhydroxides that can occur as cemented sandstone or conglomerate or as ferruginous duricrust (Yager et al., 2005; Beauvais, 1999). They are clast- or matrix-supported and typically cemented by goethite or hematite. Ferricretes are prominent features in many Questa alteration scars (Graf, 2008) and have been encountered in drill holes in the front rock piles and in a limited number of rock-pile samples from GHN, the front rock piles, and underlying colluvium. Ferricretes in the rock-pile samples are orange to brown in color and usually exhibit an overall angular to subangular shape (Fig. 7).

### Cementation in the hot zones

Cementation appears to increase in the hot zone in SI-50 (Fig. 8). 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 55°C). Deeper in the hot zone, cementation increased (sample SSS-EHP-0018, depth 159-169, approximately 63°C). 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 30°C). 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 (DRA-7; McLemore et al., 2008f).

### **Cementation in the natural analogs**

In the residual weathering profiles in the alteration scar and in the bedrock beneath GHN (DRA-20, 21; Ludington et al., 2005; Graf, 2008; McLemore, 2008a), weathering increase upwards through the weathering profile. The rock material at the base of the profile is fractured bedrock and becomes more fragmented and soil-like with smaller rock fragments in a soil matrix (i.e. matrix supported) towards the top of the profile; and shows a decrease in particle size from unweathered to weathered samples (Ludington et al., 2005; Graf, 2008; McLemore, 2008a). Cementation is variable in the alteration scar profiles, is similar to that observed in the rock piles (Fig. 9), and is attributed to the precipitation of gypsum, jarosite, and Fe-oxide minerals.

Weathering and diagenetic processes (especially cementation) have occurred in the debris flow, which are similar to that found in the rock piles. Figure 10 shows the texture and mineralogy of the cementation found in the debris flow, which is similar to that found in the Questa rock piles (Fig. 1-6).

### **Cementation and cohesion as determined by in-situ testing**

In-situ test sites were chosen in the Goat Hill debris flow (also known as Goat Hill Gulch) and Questa Pit alteration scar in order to determine if cohesion and friction angle differed between the older analog sites and the rock piles. Several areas also were selected in the Questa rock piles with variations in hydrothermal alteration and weathering. DRA-47 discusses the in-situ test results. There is a statistically significant difference (using a one way ANOVA, analysis of variance) in cohesion between the alteration scar, debris flow, and Questa rock piles ( $P = <0.001$ ); the alteration scar (2 samples) and debris flow (2 samples) have higher cohesion values than the rock piles (20 samples) (DRA-47). The cementation in the rock-pile and analog samples with higher cohesion values are a result of intergrown jarosite and clay minerals (Figs. 11, 12). Samples with lower cohesion values have slightly lesser amounts of jarosite and clay minerals as cementing minerals (Fig. 13). Cementation is only one part of the cohesion value.

### **Cementation in the humidity cells**

Humidity or weathering cell experiments are kinetic or accelerated weathering tests, which attempt to mimic natural oxidation reactions. The samples are subjected to dissolution and the results can be used to estimate the potential quality of drainage from the material and to estimate the rates of mineral oxidation and dissolution. Detailed mineralogical analysis and description of the original material and the leached solids are important in understanding the effects of the test conditions on weathering of the materials. Samples for the University of Utah humidity cell tests were selected based on differences in lithology and total sulfide content. Two representative lithologies were selected and a fresh and a weathered example of each lithology tested, with weathering determined based on visual observation. Four fresh rhyolite and four fresh andesite samples and three weathered rhyolite and three weathered andesite samples, each with varying amounts of pyrite were selected. The samples were characterized before and after the humidity cells experiments (DRA-34; McLemore et al., 2008d).

Some of the samples after the humidity cells experiments were moderately to well cemented (Ed Trujillo, personal communication, June 2008). The majority of the samples

show a decrease in CaO, SO<sub>4</sub>, Cu, Zn, gypsum, and jarosite (if present in the original sample) after the sample was subjected to the humidity cells experiments compared to the original sample (DRA-34; McLemore et al., 2008d). Microprobe analyses indicate the changes to the samples in the weathering cells are subtle. Several samples, including GHN-KMD-0088 and GHN-KMD-0057, appear to have a higher concentration of Fe-oxide cementation than the original samples before the humidity cells (Fig. 14, 15). In several samples, there appears to be slightly more Fe-oxide intergrown with clay minerals in the samples that have been in the weathering cells. Jarosite is typically minor in the humidity cells and does not appear to be a major cementing mineral.

## **6. RELIABILITY ANALYSIS**

### **Assumptions/Limitations of Petrographic Characterizations**

The primary limitation of the data lies in the estimation of mineral abundances, lithology abundances and alteration intensity. The American Geological Institute (AGI) provides the comparison charts that we use to estimate volume abundance of minerals and lithologies. This estimation may vary slightly from user to user; hence the dataset is only semi-quantitative. Moreover, there is no set protocol to determine alteration intensity, thus this data may vary widely between different petrographers. Like the electron microprobe analysis, the petrography data is collected on a relatively small sample, i.e. hand-sample sized to fine-grained sand sized particles. We recognize that the data obtained from these analyses may not be completely representative. However, we assume the interpretations can be applied to the larger scale rock pile.

The principal limitation of the electron microprobe data is that the samples analyzed are very small, and therefore cannot fully represent the entire spectrum of mineral compositions, morphologies and textures present within a given rock pile unit. The assumption made as part of microprobe analysis is that, although our samples are small, the interpretations made from our analyses are relevant, and provide insight into processes occurring in the rock piles. The presence of neo-formed minerals themselves do not constitute evidence for cementation. To create cementation the minerals must form at the contacts between grains.

Samples collected 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 DRAs and described in more detail in McLemore and Frey (2008).

## **7. CONCLUSIONS OF THE COMPONENT**

Cementation at the formation of the rock piles was zero, so any cementation documented in the rock piles is the result of weathering. The amount of cementation is generally estimated in the field descriptions (Access database) and also is estimated in the petrographic analysis of samples (DRA-4, 6). Authigenic gypsum, jarosite, soluble efflorescent salts, Fe-oxide minerals and 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 and analog materials (DRA-2, 6; McLemore et al., 2008a). Cementation in general is similar, in morphology, texture, and mineralogy, in the rock-pile and analog (bedrock, alteration scar, debris flow) materials. In general the amount of cementation is variable, but the debris flows do tend to be more cemented

(DRA-22, 47). The in-situ tests confirm higher cohesion values in the debris flow and alteration scar samples compared to the rock-pile materials (DRA-47). The shear strength would be expected to increase with increase in cementation. Samples tested in the humidity cells also showed evidence of cementation, where Fe-oxides and clay minerals cemented the material after humidity cells testing and was similar to that found in the rock piles (DRA-34; McLemore et al., 2008d). There also is a question about the durability and long term stability of these cementing minerals. Given that they are stable in the current acidic pore fluids that can be expected to remain as long as pyrite remains in the pile, we do not consider them ephemeral.

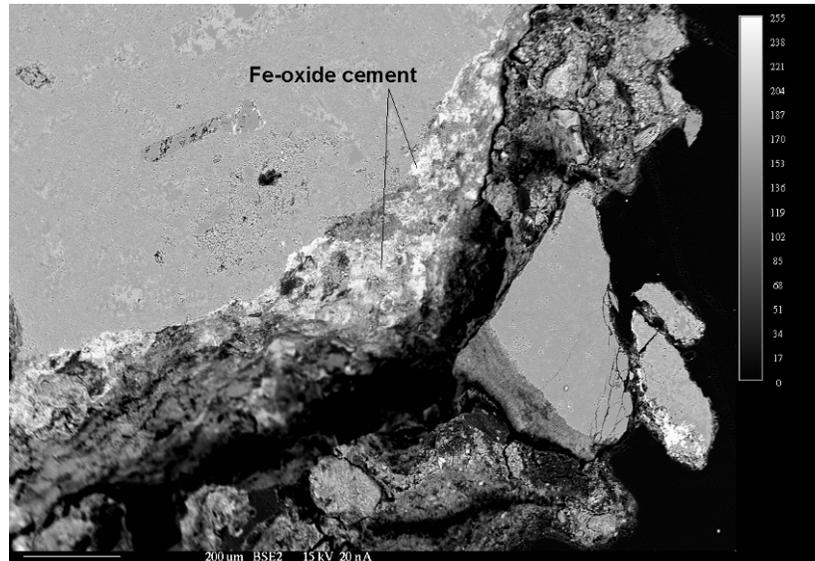


FIGURE 1. Backscattered electron image showing tabular Fe-oxide cement intergrown with clay in soil matrix (Image GHN-NWD-0014-30-02, Goathill North rock pile).

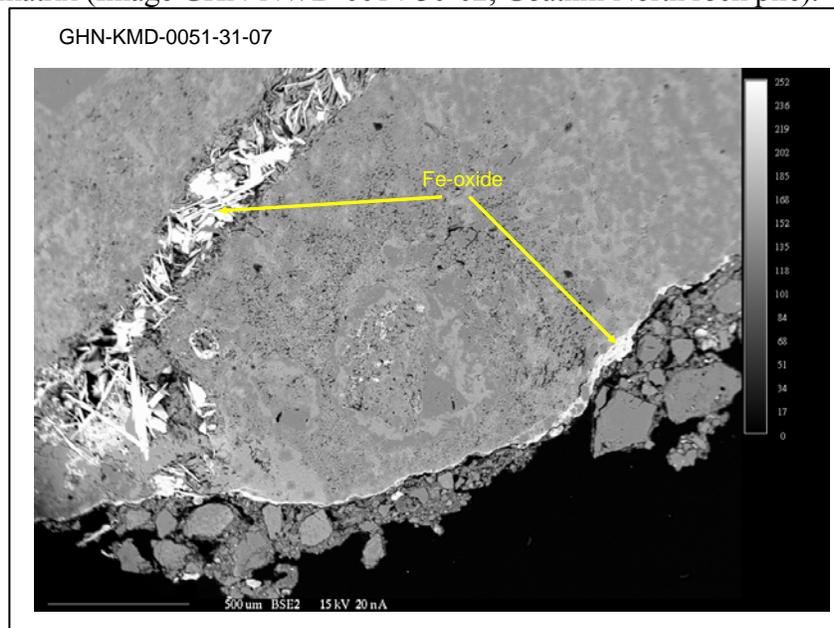


FIGURE 2. Backscattered electron image showing Fe-oxide cement (bright areas) intergrown with clay in soil matrix (Image GHN-KMD-0051-31-07, Goathill North rock

pile). This delicate bladed morphology is likely post-mining weathering because these bladed crystals probably would not withstand blasting, hauling, and end-dumping.

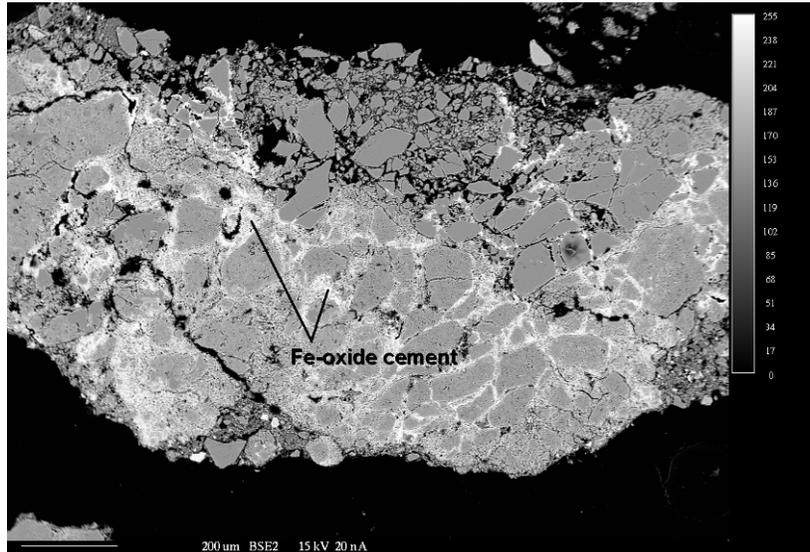


FIGURE 3. Backscattered electron image showing Fe-oxide cement (bright areas) intergrown with clay in soil matrix (Image GHN-NWD-0020-30-08, Goathill North rock pile).

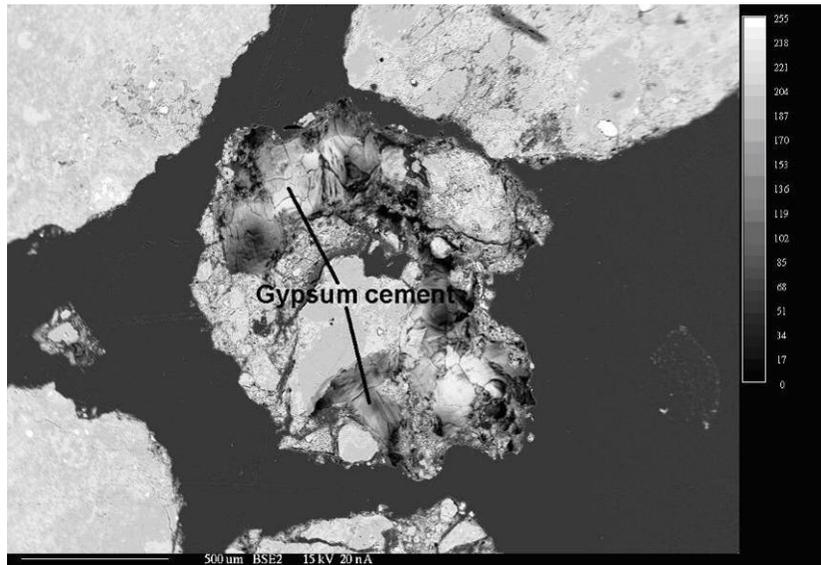


FIGURE 4. Gypsum cement intergrown (mottled gray areas) with soil matrix (Image GHN-NWD-0024-30-05, Goathill North rock pile).

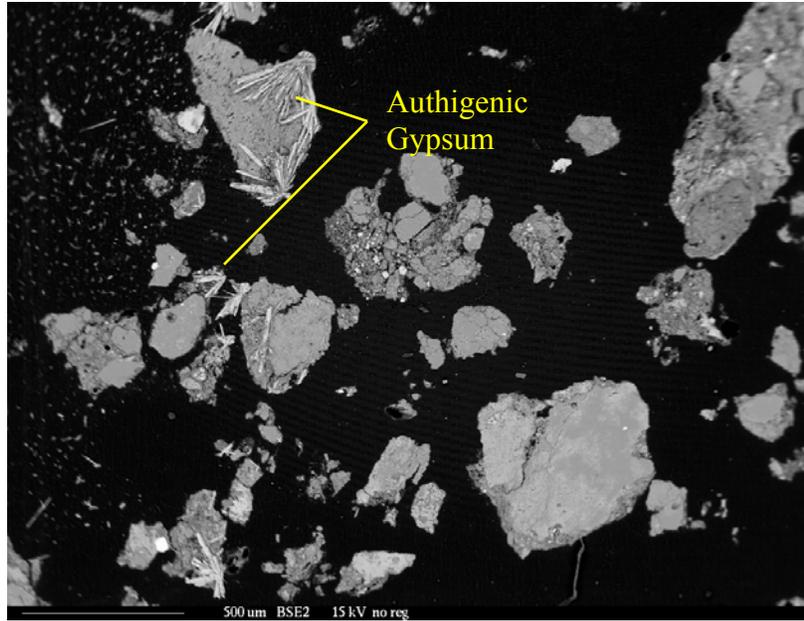


FIGURE 5. Backscattered electron image of rock pile sample from unit I, GHN (Goathill North rock pile). Bladed, prismatic crystals are authigenic gypsum.

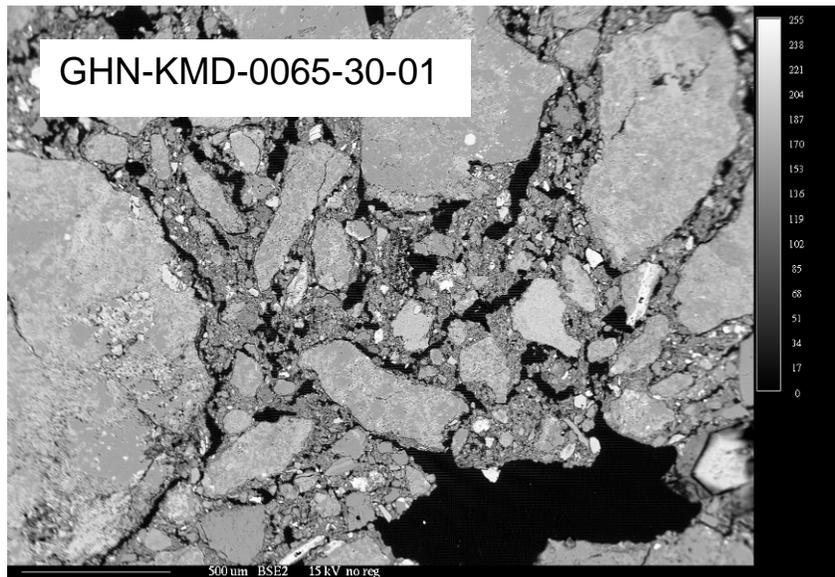


FIGURE 6. Backscattered electron image (BSE) showing soil sample showing rock fragment and associated fine-grained matrix material in the GHN rock pile. The fine-grained matrix consists of clay minerals and gypsum.

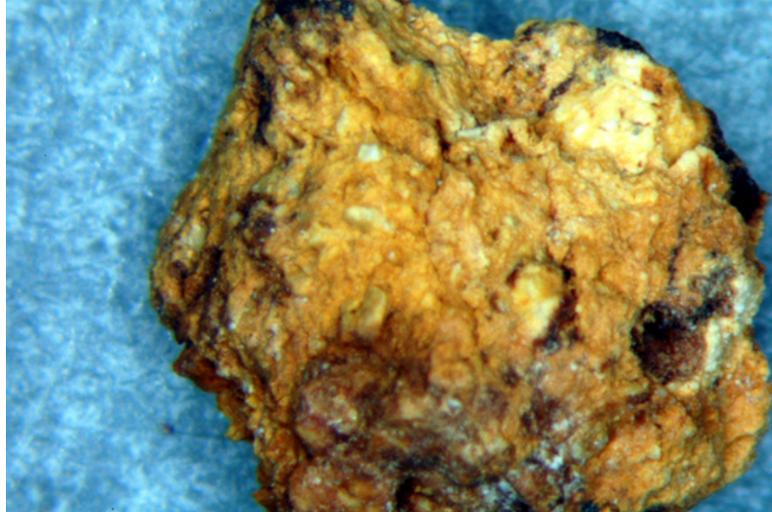


FIGURE 7. Ferricrete from GHN rock pile. Field of view is 6 mm. Photo number is GHN-VTM-205-T003.

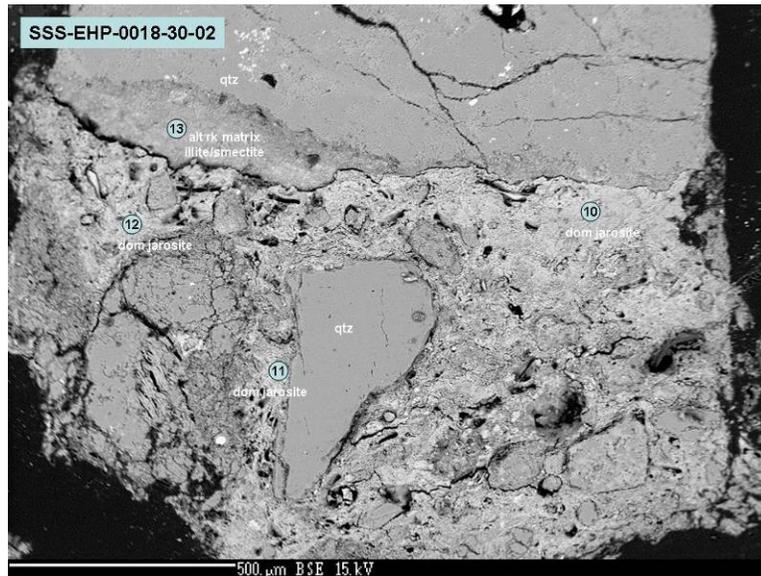


FIGURE 8. Backscattered image of sample SSS-EHP-0018-30-02 from the hot zone in SI-50, Sugar Shack South rock pile, showing a close-up of jarosite-cemented clast (depth 159-169 ft, approximately 60°C).

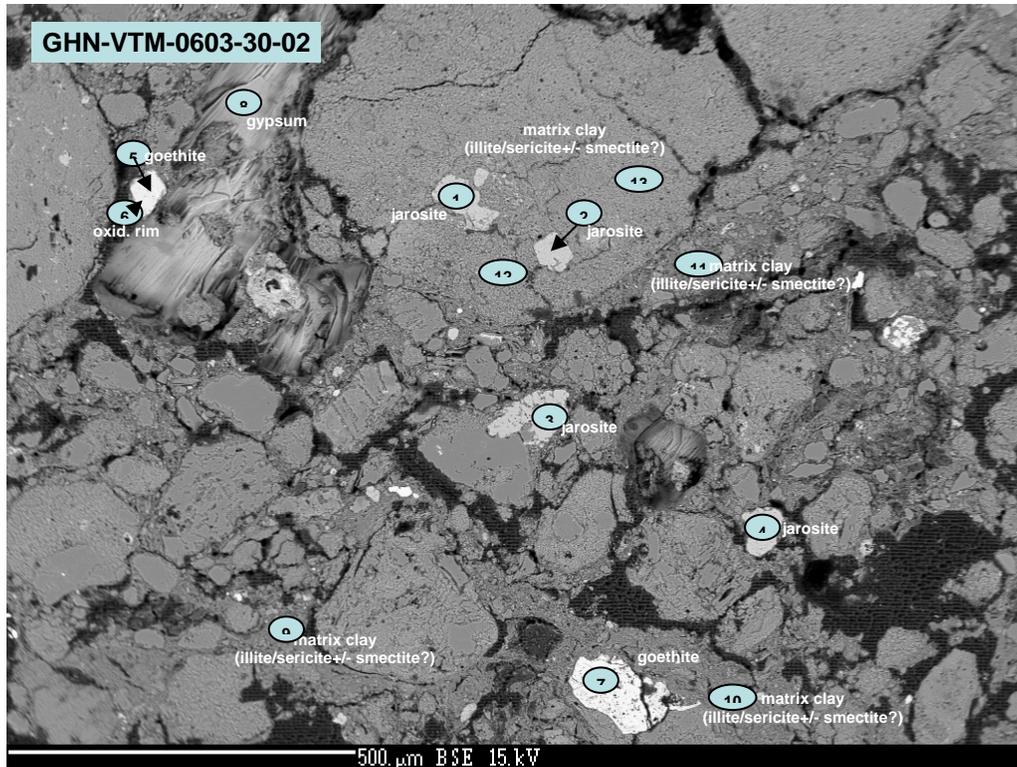


FIGURE 9. Backscattered electron microprobe image within weathered andesite profile showing hydrothermally altered phenocrysts and cemented rock fragments, which is similar to that found in the rock piles (McLemore, 2008a). Blue ovals represent points for mineral chemistry. Note jarosite and gypsum crystals.

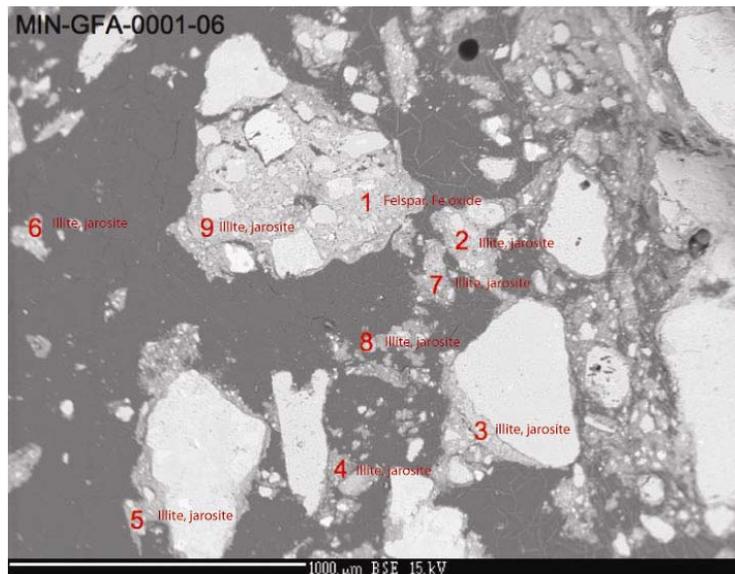


FIGURE 10. Backscattered electron microprobe image showing hydrothermally-altered phenocrysts and well-cemented grains within MIN-GFA-0001 sample from the debris flow profile. The numbered points represent points for mineral chemistry. Illite, jarosite

and Fe oxide crystals are cementing the rock fragments. The cementation is similar in chemistry and texture as that found in the Questa rock pile (Figs. 1-6).

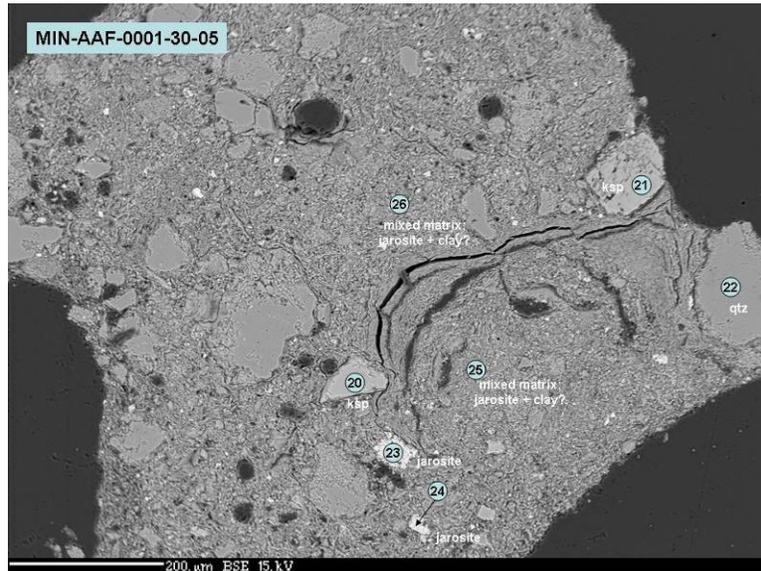


FIGURE 11. Backscattered electron microprobe image showing well-cemented rock fragments, cemented by intergrown jarosite and clay minerals in sample MIN-AAF-0001-30-05 (debris flow), in-situ cohesion=31.39 kPa.

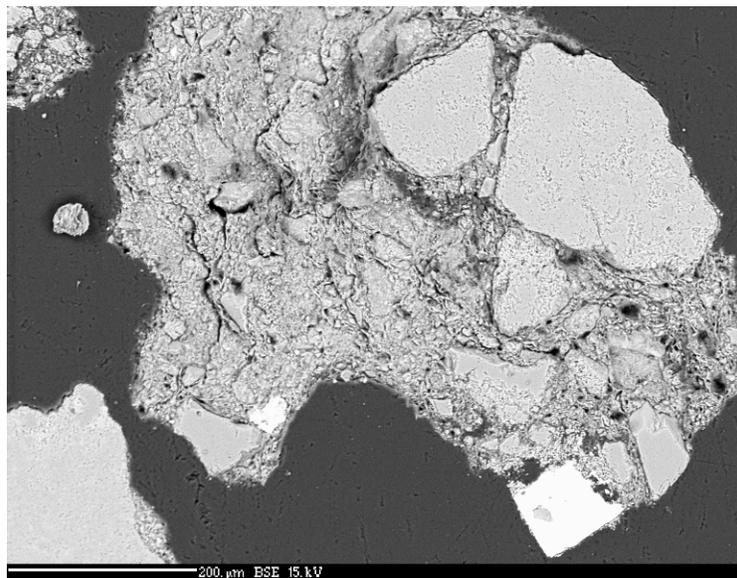


FIGURE 12. Backscattered electron microprobe image showing clay-cemented rock fragments and pyrite grains (bright white cubes), sample SSW-VTM-0600-30-06 (Sugar Shack West rock pile), in-situ cohesion=19.29 kPa.

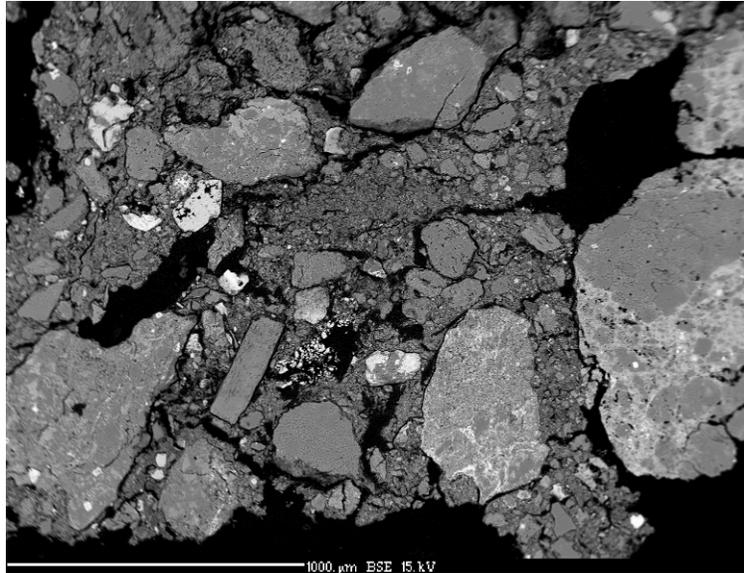


FIGURE 13. Backscattered electron microprobe image showing not as well-cemented rock fragments and pyrite grains (bright white cubes) as shown in Figures 11 and 12. The cementing minerals are clay minerals, Fe-oxides and jarosite in sample SSS-VTM-0600-30-01 (Sugar Shack South rock pile), in-situ cohesion=1.87 kPa.

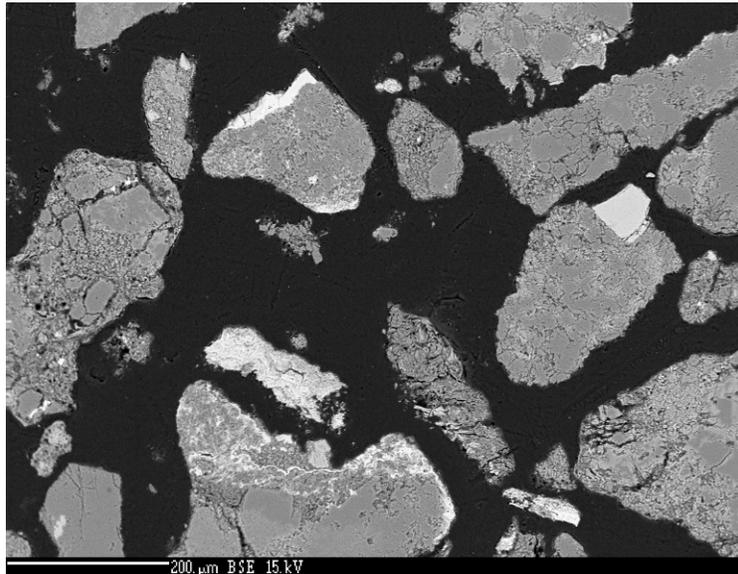


FIGURE 14. BSE of sample GHN-KMD-0088-33 showing Fe-oxide cementing rock fragments after humidity cell testing (Goathill North rock pile).

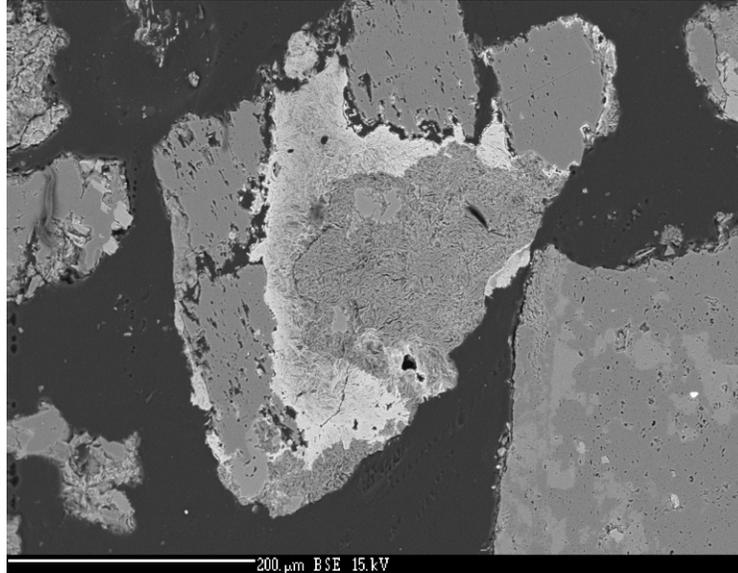


FIGURE 15. BSE image of sample GHN-KMD-0057-34 showing Fe-oxide cements after humidity cell testing (Goathill North rock pile).

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