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CLAY MINERALOGY OF THE GOATHILL NORTH ROCK PILE, QUESTA MINE, TAOS COUNTY, NM: ORIGINS AND INDICATIONS OF IN-SITU WEATHERING

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ABSTRACT

Clay minerals play an important role in the gravitational stability of man-made rock piles by affecting geotechnical and hydrological characteristics of the material. The Goathill North rock pile at the Questa Mine in northern New Mexico has been the focus of a multi-disciplinary study to determine the effect of weathering on rock pile stability and in particular to determine if clay minerals are forming in the rock pile due to surface weathering. The results of x-ray diffraction (XRD) and scanning electron microscopy (SEM) analyses indicate the clay minerals found within the fine-grained soil matrix of the rock pile are of hydrothermal origins and did not detect any neoformation of clay minerals. The foremost mechanism for an increase in clay minerals within the rock pile is the physical break down of hydrothermally altered rock fragments to release hydrothermal clay minerals. The hydrothermal clay minerals within the rock pile show evidence of weathering by the dehydration of smectite from 2-water to 1-water interlayers within the clay mineral structure. This dehydration is most likely due to higher temperatures and low relative humidities in the Goathill north rock pile during surface exposure.

INTRODUCTION

The gravitational stability of rock piles and other man-made earthen structures is a critical issue to the mining industry for planning, operation, closure and post-closure activities. The term rock pile refers to the man-made structures of non-ore bearing material removed during open pit mining. Rock piles are also referred to as sub-ore, mine waste, waste rock, or overburden material. Understanding the origins, mineral type, abundance, and distribution of clay minerals is necessary to characterize the hydrological and geotechnical properties of a rock pile. Furthermore understanding how and at what rate clay minerals may form in the near- or long-term future will determine if clay minerals will affect the stability of a rock pile as it is exposed to surface weathering.

The Goathill North rock pile at the Questa molybdenum mine in northern New Mexico is the subject of a large-scale study to determine the affect of weathering on long-term gravitational stability. The clay minerals within the fine-grained soil matrix material of the rock pile will have significant impact on the hydrologic and geotechnical properties of the rock pile. There are two possible origins for the clay minerals in the rock pile material, either hydrothermal and supergene alteration prior to mining or surface weathering of primary silicate minerals after the construction of the rock pile. The purpose of this investigation was to determine the origin of the clay minerals in the fine-grained soil matrix material of the Goathill North rock pile.

Weathering is defined as the disintegration of rock by physical, chemical, and/or biological processes that result in a change in the original mineralogical composition or physical nature of the rock. For the purpose of this study, weathering refers to the changes in the rock-pile material since the rock pile was constructed. Supergene alteration is defined as weathering of an ore deposit at or near the surface after the hydrothermal activity has ceased and is not included in the term weathering for this study, but is considered part of the pre-mining alteration. There is evidence of in-situ weathering occurring in the Goathill North rock pile since it was constructed. Recently formed sulfate minerals have been discriminated from hypogene and ancient supergene sulfate minerals using stable isotopic and textural studies (Campbell and Lueth, 2007). The neoformation of sulfate minerals is an indication of sulfide oxidation and weathering occurring since Goathill North rock pile was constructed.

REGIONAL GEOLOGY

The Questa molybdenum mine is located between the towns of Red River and Questa in northern New Mexico (Figure 1). The geology and mining history of the Questa area has been previously described in greater detail by others (Carpenter, 1968; Clark, 1968; Lipman and Reed, 1989; Meyer and Leonardson, 1990, 1997; Czamanske et al., 1990; Roberts et al., 1990; Meyer, 1991; Meyer and Foland, 1991). The Questa-Red River area is located within the Latir volcanic field on the southern portion of the Questa caldera (Lipman and Reed, 1989). The Proterozoic basement rocks of meta-sedimentary and meta-igneous rocks are overlain by Tertiary sediments and late-Oligocene volcanic rocks of the Latir volcanic field (Lipman et al.,1986). The Latir volcanics consist of alkaline basaltic andesites and volcanoclasitics to peralkaine rhyolites and ash-flow tuffs. Granitic plutons and porphyrtic dikes intrudied along the southern margin of the caldera were the primary source for the hydrothermal fluids that led to the molybdenum mineralization and district-wide pyritization (Leonardson et al. 1983).

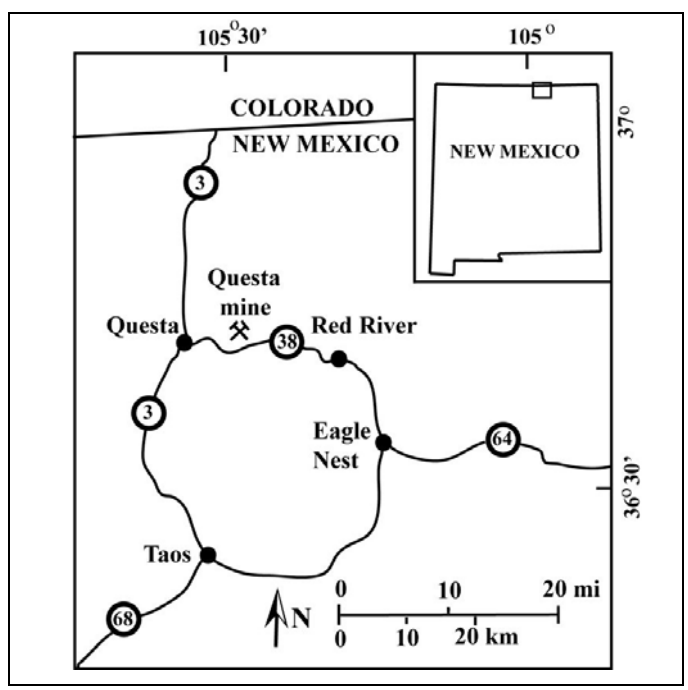

Figure 1. Location map of the Questa mine in northern New Mexico.

The Questa molybdenum deposit is considered to be similar to a Climax-type deposit (Ludington et al., 2005). The Climax-type molybdenum deposits are characterized by the genetic relationship to fluorine- and silica-rich porphyrtic and grantic intrusive rocks (Guilbert and Park, 1986). The hydrothermal alteration within a Climax-type deposit consists of several alteration shells that extend outward from the source intrusion. The alteration zones from near the intrusion outward consists of potassic alteration, followed by quartz-sericite-pyrite (QSP) alteration, and then most distal to the intrusion is propylitic alteration. The QSP-alteration is similar to phyllic alteration and consists of quartz, pyrite, and sericite. The term sericite is a field term used to describe the minerals illite, sericite, hydromuscovite and/or muscovite. The propylitic-alteration mineral assemblage consists of chlorite, epidote, pyrite, quartz, and carbonate minerals. The propylitic alteration is best developed in the andesite and quartz latite lithologies due to higher amounts of Ca-, Mg-, and Fe-bearing igneous minerals to transform into chlorite and epidote (Ludington et al., 2005). The rhyolite porphyry and tuffs generally lack signs of propllytic alteration, which are in part to due to the lack of Ca-, Mg-, and Fe-bearing igneous minerals or may be that these lithologies were erupted after the propylitic alteration occurred (Ludington et al, 2005). The QSP–alteration typically overprints the propylitic alteration in the andesites with the propylitic mineral assemblages being partially to completely replaced.

DESCRIPTION OF STUDY AREA

The Goathill North rock pile is one of nine rock piles on the mine site as a result of open-pit mining. Open-pit mining and overburden removal began in 1964 and ended in 1982 when the mine resumed the underground mining operation (Schilling, 1960, 1990; Ross et al., 2002; McLemore and Mullen, 2004). Approximately 317.5 million metric tons of overburden rock were excavated and deposited onto mountain slopes and into tributary valleys forming the rock piles during open-pit mining (URS Corporation, 2003). The process of excavating the rocks from the open pit and dumping them into the rock piles resulted in a wide range of particle-sizes from large boulders (several feet wide) to silt and clay-size particles mixed together. The rock pile material can be described as hydrothermally altered rock fragments within a fine-grained soil matrix exposed to surface conditions and weathered. The two dominant rock fragment lithologies in the Goathill North rock pile are andesite and rhyolite tuff. The two predominant types of hydrothermally alteration are qurtz-sericite-pyrite (QSP) and propylitic.

Part of the Goathill North rock pile was unstable and had been creeping down slope since its construction (Norwest Corporation, 2003). The mitigation plan for the unstable portion of Goathill North included removing material from the top portion of both the stable and unstable areas and pushing the material to the bottom of the valley (Figure 2). During the re-grading of Goathill North, trenches were cut in the stable portion of the rock pile to collect samples and map the rock pile internal stratigraphy (McLemore et al., 2005, 2006a, b). Stratigraphic units were delineated within the rock pile based on observations made in the field such as color, grain size, rock fragment lithology, and stratigraphic position (Figure 3). The trenches were constructed only in the upper third of the rock pile during the remediation of Goathill North.

SAMPLE DESCRIPTION

Samples from the Goathill North rock pile and drill core from the mine site were studied to determine the effect of weathering on similar materials from different weathering time scales. Drill core samples represent hydrothermally-altered rocks that have not been exposed to post-mining surface weathering. The samples from the Goathill North rock pile represent hydrothermally-altered samples that have been exposed to surface weathering since the construction of the rock pile (approximately 20 to 40 years).

Drill core samples were collected as part of the exploration drilling program that began before the open pit was mined to determine the extent and the grade of the ore deposit. The drill core samples have been stored in a core shed since the holes were drilled and therefore were not exposed to surface weathering. Drill core samples were cut into thin sections for electron microprobe analyses. The remaining drill core was crushed using jaw crushers to obtain clay-sized material.

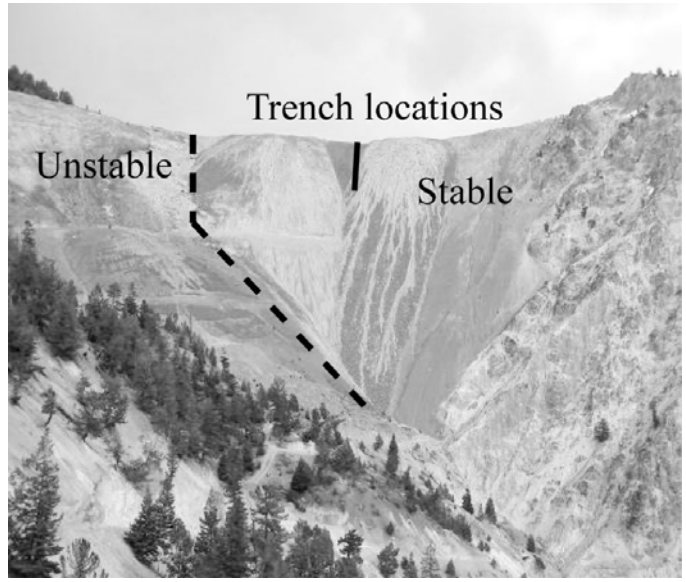

Figure 2. Photograph of Goathill North, looking East, prior to deconstruction. The dashed line represents the boundary between the stable and unstable portion of Goathill North. The solid line represents the approximate location of the trenches constructed in the stable portion of Goathill North.

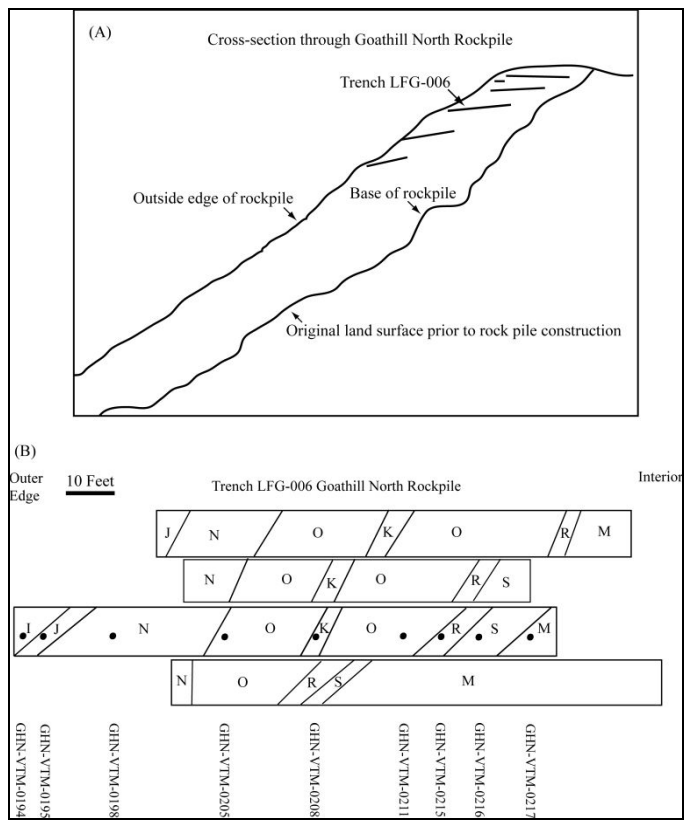

Figure 3. (A) Schematic drawing of a cross section through the Goathill North rock pile showing the location of the constructed trenches. The solid lines represent the location and length of the six trenches constructed in the stable portion of Goathill North. (B) The geologic map of trench LFG-006 shows the sample locations and described geologic units from the outer edge to the interior of the rock pile.

The samples from Goathill North rock pile were collected along a continuous horizontal profile along a single bench from the outer edge of the rock pile towards the interior of the rock pile. Samples were collected in 1-5 foot intervals within a single unit along a trench wall and multiple samples were collected from units wider than 5 feet. One representative sample from each geologic unit within bench 9 from trench LFG-006 was selected for this study (Figure 3). The samples consist of rock fragments within a fine-grain soil matrix. The rock fragment samples were split from the fine-grained soil matrix material using a number 4 sieve (4.75 mm) and prepared separately. Rock fragments were washed in de-ionized water to remove adhered fine-grained soil matrix material then air-dried. The lithology and hydrothermal alteration of the rock fragments within each unit were described as a percentage of the total rock fragments for the sample by visual inspection of the sample using a binocular scope (Figure 6). The rock fragments were crushed to analyze the clay minerals within the rocks. The fine-grained soil matrix splits of the samples were not crushed to determine the mineralogy of loose clay minerals in the fine-grained soil matrix.

SAMPLE PREPARATION AND ANALYTICAL METHODS

Electron microprobe analysis and scanning electron microscopy

Samples were prepared for microprobe analysis by placing a split of the sample in a one-inch round sample disk, vacuum impregnating with epoxy, and polishing with a series of grit polishing cloths. Electron microprobe backscattered electron (BSE) imaging and quantitative analysis were performed using a Cameca SX-100 electron microprobe. The quantitative analyses were accomplished using a 15 kV accelerating voltage and 10 nA beam current. The beam was broadened to between 20 and 25 microns in order to determine average composition of clay mineral areas. Analyses were carried out for 9 major elements: Si, Al, Ca, Mg, Mn, Fe, Ti, P, K plus S, F and Cl. Count times were 20 seconds for all elements except S and Cl (40 seconds) and F (60 seconds). Standard ZAF matrix correction techniques were used to convert net analyte intensities to element concentrations. Analytical precision was determined based on replicate analyses of standard reference materials with similar composition to unknowns.

X-ray Diffraction

Clay mineral identification sample preparation was performed using the sedimentation separation technique described by Moore and Reynolds (1997). Samples were rinsed repeatedly with de-ionized water to remove dissolved ions. However, the addition of a peptizing agent (sodium hexametaphosphate) was necessary to maintain sample dispersion during preparation. The crushed drill core and rock fragments samples were prepared using the same sedimentation techniques as the fine-grained soil matrix materials.

X-ray diffraction (XRD) analyses of the clay slides were performed using a Rigaku Geiger-flex X-ray diffractometer CuKα. Clay minerals were identified by diffraction peak locations after thermal and chemical treatments. The samples were scanned for an air-dried oriented, glycolated, and heated analysis. The sample clay slides were placed on a ceramic platform in a covered Pyrex dish containing ethylene glycol for at least 24 hours. The samples were heated to 375°C for 30 minutes to collapse the expandable clay mineral layers (Austin and Leininger, 1976). The NEWMOD modeling program was used to model the composition of mixed-layer clay minerals in the samples (Reynolds, 1985).

RESULTS

Drill Core Samples

Overprinting and different intensities of hydrothermal alteration cause a wide range of clay mineral assemblages in the drill core samples. The drill core samples can be grouped into three different groups based on the clay mineral assemblages determined by XRD analyses and the lithology and predominate hydrothermal alteration (Figure 4).

Group one consists of samples that contain mostly illite and kaolinite with no significant abundances of other clay minerals (Figure 4a). The predominant hydrothermal alteration for this group is QSP or argillic alteration of either andesite or rhyolite lithologies. Group two contains mostly illite and chlorite with minor amounts of smectite (Figure 4b). The predominant hydrothermal alteration for group two is propylitic-alteration with minor QSP overprinting of andesite. Group three contains illite, smectite, chlorite and kaolinite (Figure 4c). Group three samples consist of highly propylitic and QSP overprinting alteration of both andesite and rhyolite lithologies. The presence of jarosite (15.4° 2θ peak position) in drill core samples is evidence of supergene alteration of samples near the top of the ore deposit. The drill core samples did not contain abundant amounts of mixed-layer clays minerals in any of the rock types.

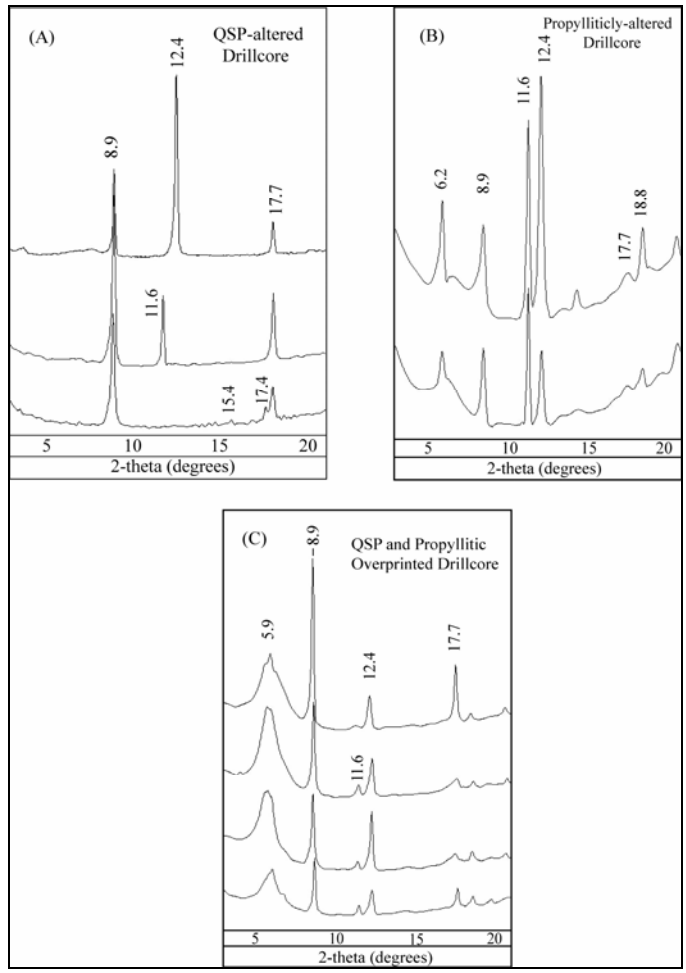

Figure 4. XRD results for the drill core samples grouped based on clay mineral type and sample lithology and hydrothermal alteration assemblages. All values are reported as 2-theta degrees. (a) QSP-altered rhyolite and andesite samples, (b) Propllytically-altered andesite samples, (c) Overprinted andesite and rhyolite samples.

The back-scatter electron (BSE) images of the drill core samples shows evidence of primary igneous minerals being replaced by clay minerals (Figure 5). An andesite sample with QSP-alteration contains isolated pockets of clay minerals enclosed within a relict igneous feldspar mineral grain. The igneous groundmass of the drill core samples also contains pockets of clay minerals and pervasive clay mineral replacement. Chlorite formed thin veinlets, locally with quartz as well as replace magmatic minerals such as biotite and feldspar. The clay minerals other than chlorite were not observed to form along fractures or as discrete veins. Clay minerals are found in spatial association with other mineral phases, such as epidote and pyrite, which are the products of hydrothermal alteration. The drill core samples from each of the three groups contain pyrite grains (brightest areas of the image) with no indication of tarnishing or being oxidized in the same proximity as clay minerals. Evidence from microprobe

analyses confirms the presence of jarosite replacing relic pyrite grains and filling veins.

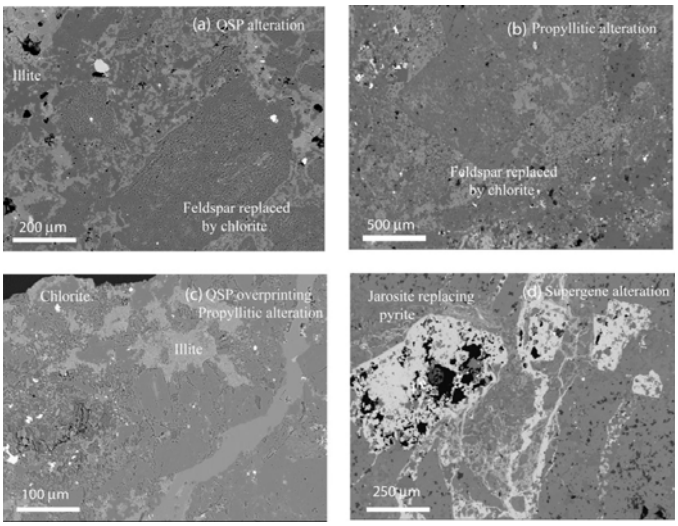

Figure 5. Scanning electron back-scatter micrographs of drill core samples. (a) QSP-altered andesite sample with relic feldspar pheocrysts replaced by clay minerals, (b) Propllytically-altered andesite sample, (c) QSP-overprinting propllytic-alteration of an andesite sample, (d) Jarosite replacing pyrite and filling veins in a QSP-altered rhyolite sample.

Goathill North rock pile samples

The XRD results for Goathill North samples indicate the illite, chlorite, smectite, mixed-layer I/S and kaolinite clay minerals found in the fine-grained soil matrix can also be found in the rock fragments (Figure 6). The XRD scans for the Goathill North samples can be grouped together into two general groups of samples based on the relative abundances of illite and chlorite from XRD analysis. The fine-grained soil matrix samples with high relative abundances of illite and low relative abundances of chlorite are from geologic units that contain higher percentages of QSP-hydrothermally altered rhyolite rock fragments. The XRD scans of the corresponding rock fragments splits also have high relative abundances of illite. Fine-grained soil matrix samples with higher relative abundances of chlorite are within geologic units that typically contain higher percentages of propylitically-altered andesite rock fragments.

XRD analysis of the mixed-layer I/S clay minerals area between the smectite (5.7 ° 2θ) and illite (8.7 ° 2θ) peaks indicates several peaks fall in the region between the pure end-member clay minerals. The fine-grained soil matrix samples have higher intensity XRD peaks in the area of the mixed-layer I/S clay minerals than the XRD scans of the rock fragments for the same units. This indicates a higher abundance of clay minerals with XRD peaks between 5.7 and 8.7° 2θ in the fine-grained soil matrix. In particular the fine-grained soils matrix samples have a distinct peak at approximately 7.1° 2θ that is typically of lower intensity in the rock fragments from the same sample (Figure 6).

Each XRD peak positions for the mixed layer I/S clay minerals can be the result of more than one possible combination of end-member clays. The NEWMOD XRD modeling program was used to calculate the XRD scan profiles for the possible mixed-layer clay minerals. The results of the NEWMOD modeling indicated the best correlation between the modeled results and the mixed-layer I/S clay minerals found at approximately 7.1° 2θ peak position is a 1W smectite. The XRD peaks at the 7.1° 2θ peak position for 1W smectite shifted to 5.2° 2θ after 24 hours of exposure to ethylene glycol and then collapse after heating to 375°C for 30 minutes confirming the presence of expandable layers. The rock fragment XRD scans for the Goathill North samples have much lower abundances of the 1W smectite than the fine-grained soil matrix of the same samples.

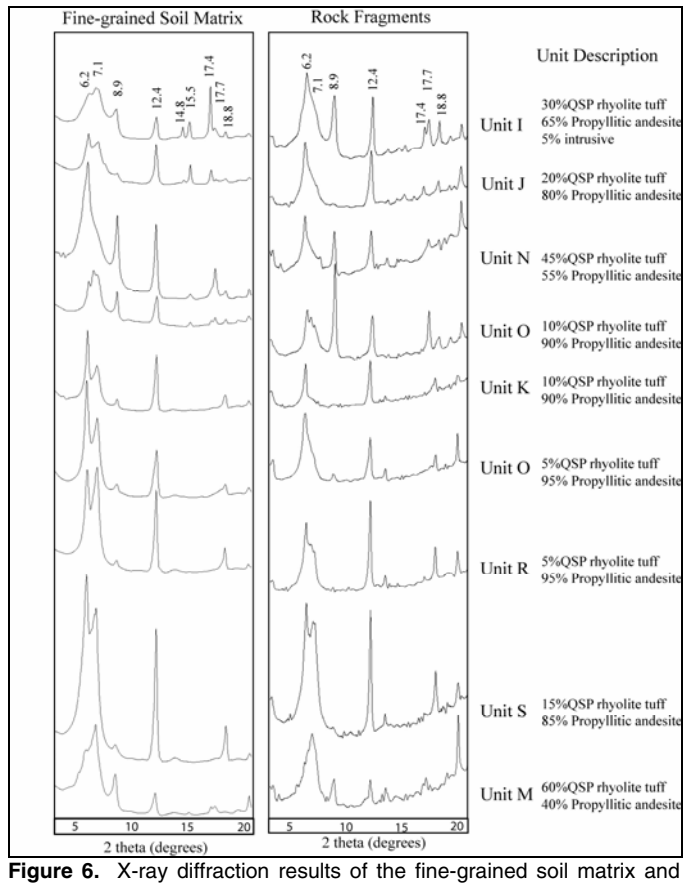

Figure 6. X-ray diffraction results of the fine-grained soil matrix and rock fragment samples from bench 9 trench LFG-006 in the Goathill Nort rock pile. Unit descriptions are of the rock fragment lithology and dominate hydrothermal-alteration estimated visually using a binocular microscope. XRD mineral peaks in degrees 2Ø: Illite = 8.9, 17.7; Chlorite = 6.2, 12.4, 18.8; Smectite = 5.2; Kaolinite = 12.4; Mixed-layer I/S = 5.2 – 8.9; Jarosite = 14.7, 15.5, 17.4, Quartz = 20.8° 2θ.

The BSE images of the fine-grained soil matrix samples from Goathill North are characterized by sand to silt-size rock and mineral fragments in a clay-size matrix (Figure 7). The contacts around the sand-size rock and mineral grains are sharp and do not indicate the in-situ breakdown of the minerals into the clay-sized matrix. Within the Goathill North fine-grained soil matrix samples untarnished pyrite grains are surrounded by clay-sized material.

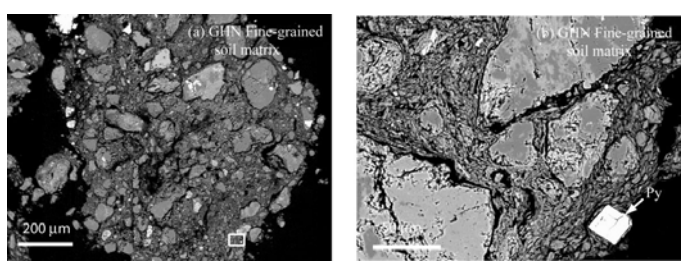

Figure 7. (a) Scanning electron back-scatter micrographs of a fine-grained soil-matrix sample from Goathill North. The white box represents the area magnified in image (b). (Py = pyrite grain).

The Goathill North clay minerals from the fine-grained soil matrix and rock fragments have similar clay mineral chemical compositions and are also chemically similar to the drill core clay minerals (Figure 8). The microprobe beam width during chemical analyses was set between 20 - 25 µm and is broader than the size of individual clay mineral grains. Therefore the clay minerals chemical analyses could represent a mixture of clay mineral phases particularly for the fine-grained soil matrix samples. The occurrence of Fe-bearing phases such as jarosite or iron-hydroxides mixed within the Goathill North fine-

grained soil matrix samples were noted by analyses with low Al and high Fe content points (Figure 8).

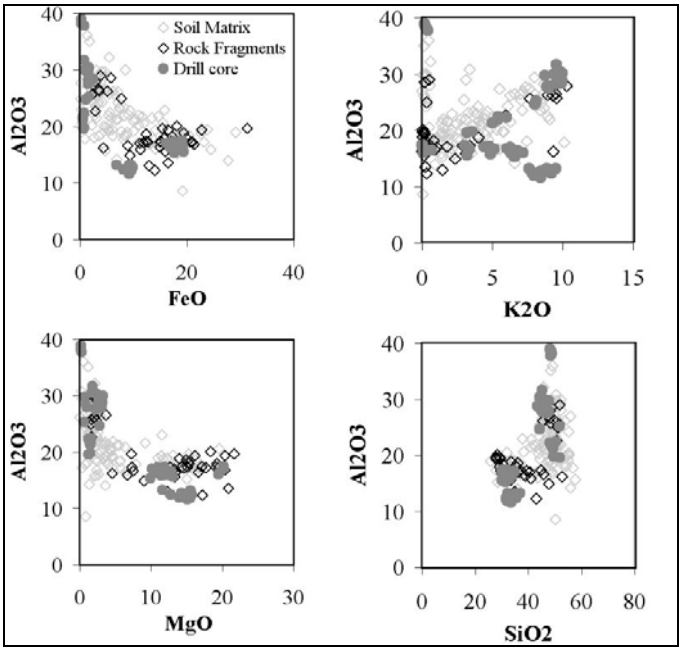

Figure 8. Plots of clay mineral chemistries determined using SEM analysis for Goathill North fine-grained soil matrix samples (open gray diamond), rock fragments (open black diamonds) and drill core samples (filled gray circles).

The drill core clay mineral chemistries determined by microprobe analyses were correlated clay minerals identified using XRD analysis. The illite clay minerals from the QSP-altered drill core samples are higher in aluminum percentages than typically reported values. However, hydrothermal illite minerals from the Bingham Canyon porphyry copper deposit have similar aluminum percentages (Parry et al., 2002). The chlorite clay mineral chemistries of the propylitically-altered samples have a range in magnesium and iron concentrations. The range in chemical composition indicates two different possible chlorite minerals (chamosite and clinochlore).

DISCUSSION

Evidence of hydrothermal origins

The process of open pit mining created the heterogeneity of the Goathill North rock pile material which is described in the different geologic units (McLemore et al, 2006a). Since the rock pile units are not homogeneous from the exterior to the interior of the rock pile, it is not possible to compare samples from the outer zone to samples from the interior of the rock pile to identify changes due to weathering. However, since the rock fragments within Goathill North rock pile are from the same material as the fine-grained soil matrix then the differences between the clay minerals within rock fragments and the fine-grained soil matrix could be an indication of in-situ weathering.

The overlap between clay mineral chemistries of the Goathill North fine-grained soil matrix and rock fragments samples indicates there is no chemical difference in the clay minerals within the rock pile material. The spread in the clay mineral chemistry data of the Goathill North fine-grained soil matrix samples is most likely the result of the several mineral phases combined during the analysis. The XRD analysis confirmed the presence of multiple clay mineral phases within the fine-grained soil matrix material. The clay mineral chemistries indicate there is no clear chemical difference between samples from the Goathill North rock pile and the drill core samples. The drill core samples have never been exposed to post-mining surface weathering conditions meaning the clay minerals within the drill core samples are the result of hydrothermal alteration.

The XRD scans for the Goathill North fine-grained soil matrix and rock fragment samples indicate the each of the major clay types (chlorite, kaolinite, illite, smectite and mixed layer I/S) are found in different proportions within each of the geologic units (Figure 6). The difference in clay mineral relative abundances appears to be correlated to the difference in lithology and alteration of the rock fragments within each unit. The rock pile units that contain a higher percentage of QSP-altered rhyolite rock fragments typically have higher amounts of illite and smectite. The rock pile units that contain a higher percentage of propylitically-altered andesite rock fragments with typically have higher amounts of chlorite.

There is no textural evidence of clay minerals forming from the break down or dissolution of the primary silicate minerals within the rock pile. The BSE imaging analysis did not find evidence of clay minerals forming at the edges of rock and mineral grain boundaries or along cleavage boundaries or as discrete clay-filled veins. The presence of untarnished pyrite grains surrounded by clay-sized materials indicates there has been no oxidation or weathering occurring in that sample to form the clay minerals in the fine-grained soil matrix surrounding the pyrite grain.

Evidence for weathering origins

There is evidence to suggest the clay minerals have undergone some degree of weathering at the surface in the Goathill North rock pile. The 1W smectite clay mineral (~7.1° 2θ) is not found in the drill core samples and is also not as abundant in the rock fragments from Goathill North indicating the formation of the 1W smectite is most likely occurring in the rock pile. An increase in the abundance of 1W smectite can be obtained at temperatures as low as 25°C with almost total dehydration of 2W smectite to 1W smectite occurring at 55°C (Ferrage et al. 2007). Relative humidity also influences the hydration state of smectites (Tamura et al., 2000). The process of smectite dehydration evolves as a two-step process with different thermodynamic thresholds for the transition from 2W-1W smectite and the transition from 1W-0W smectite (Ferrage et al., 2007). The dehydration processes is not congruent and can result in more than one hydration phase being present in a single clay mineral structure (Tamura, et al, 2000; Ferrage et al.. 2007). Modeling of samples from Goathill North indicates the possibility of multiple smectite hydration phases. The high altitude and semi-arid conditions found at the Questa mine site could be affecting the smectite hydration state of the clay minerals in the Goathill North rock pile. Ferrage et al, (2007) noted the dehydration of the smectite clay mineral was reversible up to the energy threshold where the 1W to 0W transition occurs. However the Goathill North samples did not rehydrate simply by rewetting the clay material during sample preparation. The dehydration of the smectite clay minerals could decrease the smectite clay minerals susceptibility to dissolution at low pH. The dissolution rate of smectite decreases as the number of dehydrated (non-swelling) smectite mineral layers increases (Komadel et al., 1996).

The high abundance of 1W smectite found in the rock fragments of the sample from the inner most unit (Unit M) could be an indication of supergene weathering prior to being placed in the rock pile. The rock pile material closest to the base of the rock pile is the material that was first stripped off of the open pit deposit and had the highest degrees of supergene alteration. Another possible explanation for the increase in 1W smectites is an increase in the temperature in the rock pile. Other rock piles on the Questa mine site have localized hot zones at various depths due to the exothermic reaction of pyrite oxidation (Norwest, 2005).

CONCLUSIONS

The clay minerals in the upper portion of the Goathill North rock pile fine-grained soil matrix are predominantly from hydrothermal alteration and are not formed by weathering silicate minerals. The clay minerals found within the fine-grained soil matrix are the result of breaking apart of hydrothermally altered rock. For samples from Goathill North the physical breaking of the rock occurred during mining activities. The possibility of a significant increase in the percent of clay minerals in the rock pile would most likely be due to physical weathering of the rock fragments remaining in the rock pile material.

Geotechnical testing (point load, slake durability, and direct shear tests) of the rock fragments within the Goathill North rock pile indicate the rock fragments have high durability and strength even after having undergone hydrothermal alteration and blasting prior to deposition and after potential exposure to weathering for about 40 years (Viterbol, 2007; Gutierrez et al., 2008). The possibility of an increase in clay mineral percentage due only to chemical weathering in the rock pile is very low. It is possible that neoformation of clay minerals due to the dissolution of silicate minerals is occurring in the rock pile. However, if new clay minerals are forming it is in such small amounts that the techniques used for this study cannot distinguish the newly formed clay minerals from the hydrothermal clay minerals.

The 1W smectite clay mineral found in the fine-grained soil matrix of the rock pile samples suggests weathering of the smectite clay minerals has occurred since the rock pile was constructed. The weathering occurring is the dehydration of inter-layer water from the smectite minerals most likely due to the exposure to relatively low humidity and moderate to high temperatures in the rock pile. The occurrence of the 1W smectite in each of the units for the fine-grained soil matrix samples indicates the dehydration is not restricted to the exterior units of the rock pile. The abundance of 1W smectite in the interior units of the rock pile could be an indication of high temperatures at the base of Goathill North or the 1W smectite could have formed during supergene alteration of the material prior to the rock pile construction. In the absences of temperature information for the Goathill North rock pile it is not possible to determine which process is more likely.

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