

Geologic Processes Affecting the Chemistry, Mineralogy, and Acid Potential on Particle Size Fractions: Examples from Waste Rock Piles in New Mexico, USA

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Abstract

Four projects in New Mexico have examined the geologic processes affecting the chemistry, mineralogy, and acid potential of different particle size fractions of samples collected from rock piles and natural materials. The finer-size fraction, typically <25% of the sample, is generally higher in trace elements and certain minerals. Total clay minerals, gypsum, and jarosite are higher in the finer-size fraction. In some samples, calcite and pyrite decrease in the finer-size fractions. For some samples, paste pH values decrease from the coarser-size fraction to the finer-size fraction. For most samples the coarser-size fractions are less acid generating than finer-size fractions. No single process is responsible for these differences in composition between size fractions. Primary igneous crystallization, pre-mining hydrothermal alteration, and post-mining emplacement into the rock pile and subsequent weathering affect the composition of each size fraction. This emphasizes the need to determine not only the composition of the different size fractions, but also perform detailed mineralogy and petrology investigations to understand the processes involved in controlling the compositional differences between size fractions. Although the results are generally consistent, there is still variation between samples and it is recommended that composition of different particle sizes be examined at other sites.

Key words: stream sediments, soils, weathering, Questa, Pecos, Hillsboro

Introduction

Understanding the distribution of minerals and major and trace elements in different particle size fractions is important to understand the mobility and availability of minerals to dissolution and oxidation during weathering. In most geologic materials, the composition of the different size fractions is a result of the composition of the parent material and the geologic, geochemical, and pedological processes responsible for the formation of the geologic materials, as well as post-mining blasting, hauling, dumping, and emplacement into the waste rock pile. Composition of various size fractions provides an insight into what chemical changes can be expected as geological materials break down to smaller particles. Weathering of minerals involves mostly surface reactions and the rates of these reactions depend upon the available reactive surface area of the mineral. Mineral surface area is dependent upon the mineralogy, the extent to which the mineral is liberated from the rock matrix, particle size (especially mineral grain size), particle shape, and the surface morphology (i.e. roughness of the mineral surface; Lapakko et al., 1998; Lapakko, 2003). Furthermore, when mineral surfaces are covered with coatings, such as Fe oxyhydroxides, oxidation and dissolution of the mineral can be inhibited. Thus, particles of different sizes expose different proportions of the surfaces for chemical reaction, which plays an important role in weathering.

Numerous studies have examined the variations in composition between different particle size fractions, but few studies examine the geologic processes controlling these compositional changes. Strömberg and Banwart (1999) showed large differences in weathering rates between fine waste rock material and larger particles (diameters >0.25 mm) at the Aitik copper mine in northern Sweden and found that waste rock with diameters less than 0.25 mm (27% of the total mass) accounts for 80% of both the sulfide and silicate weathering. In addition, they found that calcite within grains larger than

5-10 mm reacts too slowly to neutralize the acid produced from the sulfide minerals. Taboada et al. (2006) showed that Zr and Ti behave differently in residual weathering soil profiles; Zr is enriched in the silt fraction, whereas Ti is enriched in the silt and clay fractions and depleted in the sand fraction. Dultz (2002) cautions that normally, feldspars are found in the coarser fractions of soils, but breakdown of feldspar grains by physical weathering could increase the surface area and therefore, increase the reactivity of the grains to weathering. Dultz (2002) also notes that the parent material affects the weathering of feldspars. Acosta et al. (2011) examined the major and trace element concentrations of different particle size fractions in soils derived from eight different lithologies and found that lithology and mineralogy control the concentrations of major and trace elements in the different size fractions. Dinelli et al. (2007) found that the effects of grain-size distribution on mineralogy and geochemistry are greater in sediments that have not undergone diagenesis, compaction, or lithification. Some chemical indices are not affected by grain size distribution, including Ni/Al, Cr/Al, and Mg/Al. Other indices are affected only in the coarse fraction, including $\text{SiO}_2/\text{Al}_2\text{O}_3$, Na/Al, Zr/Rb, Zr/V, Y/Rb, Y/V, and Ti/V (Dinelli et al., 2007).

The New Mexico Bureau of Geology and Mineral Resources (NMBGMR) has been examining the environmental effects of waste rock piles throughout New Mexico since the early 1990s, including the effects of mineralogy, chemistry, and acid potential on particle size fractions (McLemore et al., 1993, 1995; Brandvold and McLemore, 1998; Herring et al., 1998; Munroe, 1999; Munroe et al., 1999, 2000; Graf, 2008; Morkeh and McLemore, 2012). The purposes of this paper are 1) to describe the differences in mineralogy, chemistry, and acid potential between different particle size fractions from different materials (including stream sediments, waste rock piles, and natural soils) in selected areas of New Mexico, and 2) to discuss some of the geologic, geochemical, pedological or man-influenced processes that controlled these changes between the different particle sizes.

Site descriptions

Compositional changes between different size fractions of waste rock piles and other materials were examined in four separate areas in New Mexico over the years; including the Pecos mine and Alamitos Canyon mill in San Miguel County, Hillsboro district in Sierra County, Questa molybdenum mine in Taos County, and 6 mining districts in Socorro, Sierra and Otero Counties (Fig. 1). The four studies examined both man-made waste rock piles and natural materials (stream sediment, debris flows, alteration scars). These studies also examined materials of different lithologies and deposit types. Only the Questa molybdenum mine is currently in production, however, efforts are underway to permit and reopen the Copper Flat copper mine in the Hillsboro district. The Pecos mine and Alamitos Canyon mill have been reclaimed. The other sites sampled are inactive. The Pecos and Questa mines are found in the Sangre de Cristo Mountains in northern New Mexico, where elevations range from 2,000 to over 3,600 m and the climate is semi-arid and alpine, with cold snowy winters and moderate warm summers. The Hillsboro and other 6 mining districts are in southwestern New Mexico where elevations are lower (1,500 to 2,400 m) and the climate is arid, with moderate winters and hot summers. Monsoons occur during July and August throughout New Mexico.

Pecos mine and Alamitos Canyon mill, San Miguel County

The Pecos mine and Alamitos Canyon mill in San Miguel County were identified by state and federal agencies as point sources of contamination for Pb, Zn, and Cu. Both sites are along the Pecos River, which is a major source of water for irrigation, industrial and municipal uses in eastern New Mexico, west Texas, and Mexico (Fig. 1). The Pecos mine, a volcanic massive-sulfide deposit containing Pb, Zn, Cu, Ag, and Au, is the largest mine in the area. Waste rock generated during mining activities (1902-1944) was piled at the Pecos mine and was a source of acidic drainage that carried elevated concentrations of metals into the Pecos River before reclamation. The ore from the mine was transported by aerial tramway to the Alamitos Canyon (El Molino) mill 18 km south of the mine. This mill site also was a source of acidic drainage that carried elevated concentrations of metals before

reclamation. In addition, material from the mine waste rock pile was used as fill in roads and campgrounds throughout the upper Pecos River area and also was a source of metals entering the Pecos River. Several fish kills occurred at the Lisboa Springs Fish Hatchery, south of the Pecos mine, since 1991 that were attributed to drainage from the Pecos mine. Studies have shown that stream sediments from the Pecos River are elevated in Cu, Pb, and Zn below the Pecos mine and Alamitos Canyon mill sites (McLemore et al., 1993, 1995; Popp et al., 1996). Zinc also was elevated in the area of the Lisboa Springs Fish Hatchery. Reclamation of the Pecos mine, campgrounds, roads, and Alamitos Canyon mill site began in the early 1990s and is completed.

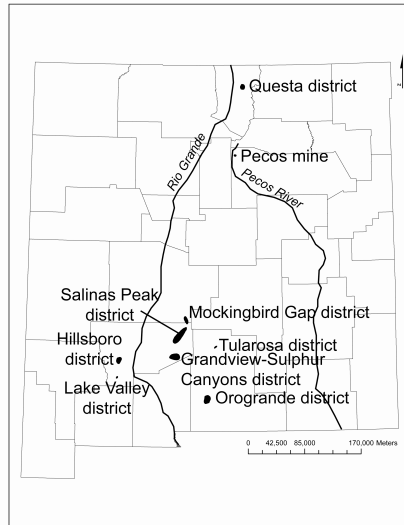


Figure 1. Location of mining districts in New Mexico where studies of mineralogy, chemistry, and acid potential on particle size fractions were performed and are summarized in this report.

Hillsboro district, Sierra County, New Mexico

The Hillsboro district in southwestern New Mexico was mined intermittently over the past 120 years for base and precious metals from numerous mines of varying sizes (Hedlund, 1985; McLemore et al., 1999, 2000). The district drains into Caballo Lake along the Rio Grande, which is a major source of water for irrigation, industrial and municipal uses in central New Mexico, southwest Texas, and Mexico. Polymetallic veins are associated with latite/quartz latite dikes and both radiate outwards from the Copper Flat porphyry copper deposit, and are flanked by distal carbonate-hosted Pb-Zn and Ag-Mn replacement deposits to the south and north. Waste rock piles from four different types of deposits were sampled; including placer gold, polymetallic veins, Pb-Zn carbonate-hosted replacement deposits, and Ag-Mn carbonate-hosted replacement deposits (Munroe, 1999; Munroe et al., 1999, 2000). The Copper Flat porphyry copper deposit in the northern part of the Hillsboro district was not examined for this project.

Questa molybdenum mine, Taos County, New Mexico

The Questa molybdenum deposit is a Climax-type porphyry molybdenum deposit, which is a large, low-grade (0.1–0.2% Mo) deposit that contains disseminated and stockwork veinlets of molybdenum sulfides. The geologic, alteration, and mining history of the Questa mine area is complex and is summarized by McLemore (2009) and McLemore et al. (2009b). During the period of Questa open-pit mining (1969–1982), approximately 317.5 million metric tons of overburden rock was removed and deposited onto mountain slopes and into tributary valleys forming nine rock piles surrounding the open pit. Chevron Mining Inc. (formerly Molycorp, Inc.) sponsored an extensive multi-disciplinary study of the Questa waste rock piles in order to further understand the effects of weathering on the

stability of the Questa waste rock piles (McLemore et al., 2008, 2009a, b, c, 2010). One aspect of this project examined the chemical and mineralogical differences between different particle size fractions and also examined the differences in acid generation between different particle size fractions of samples from the Questa rock piles, debris flows, and alteration scars (Morkeh and McLemore, 2012). Graf (2008) also examined the differences in composition between size fractions of material from an alteration scar near the Questa mine. Alteration scars are natural, colorful (red to yellow to orange to brown), unstable weathering landforms that are characterized by steep slopes (greater than 25 degrees), moderate to high pyrite content (typically greater than 3%), little or no vegetation, and extensively fractured bedrock. The scars are variable in size ranging from 1 to more than 100 acres (Luddington et al., 2005; McLemore et al., 2009b).

Other mining districts in Socorro, Sierra, and Otero Counties

This study consists of geochemical characterization of waste rock piles in areas mined for Ag, Pb, Zn, and Mn in southwestern New Mexico (Fig. 1). Waste rock piles from six mining districts (Mockingbird Gap, Salinas Peak, Grandview-Sulphur Canyon, Lake Valley, Tularosa, Orogrande) were sampled (Herring et al., 1998). More detailed background descriptions of the mining history, ore occurrence, and geology are found in Lindgren et al. (1910), Harley (1934), Lovering and Heyl (1989), and McLemore (2001). Several types of mineral deposits were sampled, including barite-fluorite deposits, Precambrian vein and replacement deposits, carbonate-hosted Mn and Ag-Mn deposits, and contact metasomatic (skarn) deposits. All waste rock piles sampled were smaller in size compared to the Questa and Pecos rock piles.

Methods

Results from these four separate projects are summarized in this paper. Each project had different scopes and slightly different sampling and analytical procedures, as summarized in Table 1. Samples were dry sieved and crushed. In the Questa study, samples were selected for this study 1) to cover a range in weathering intensities, 2) to include waste rock piles and natural materials, and 3) on availability of enough of the sample volume to perform the analyses. The actual particle size fractions examined differed between projects as well. In the Questa project, the smallest size fraction examined was <0.0787 inches (< 2 mm), because one of the primary purposes of this study was to determine the effect of composition on particle size fractions for the humidity cell tests. Selected samples from Hillsboro and Questa projects were examined using a combination of petrography (using a binocular microscope) and electron microprobe analyses to determine the lithology, alteration, mineral phases, the mineral chemistry, and to examine textural relationships between mineral phases (Munroe, 1999; McLemore et al., 2008, 2009a, b, c, 2010). Refer to the specific project reports for more details.

Results—composition of different size fractions

Pecos mine and Alamitos Canyon mill, Santa Fe County

Brandvold and McLemore (1998) and McLemore et al. (1995) found that the finest size fractions (<63 μm) of stream sediments from the Pecos River contained the largest concentrations of metals (Cu, Pb, Zn). Chemical analyses of six sediment size-fractions from six sites suggested that the metals were predominantly traveling both as suspended and/or absorbed material and as larger minerals or other grains weathered from the waste rock pile and the tailings pile (McLemore et al., 1995). Statistical analyses of XRF data indicated that Cu, Pb, and Zn had a high correlation with Fe and Mg (Popp et al., 1996), suggesting that these metals were associated with iron-bearing and ferro-magnesium minerals such as magnetite, pyrite, biotite, pyroxene, hornblende, etc. In addition, Cu, Pb, and Zn in the finest size fraction (< 63 μm) had a high correlation with Al, suggesting that these metals were also associated with clay minerals. The weight percent of the size fraction had a high positive correlation with SiO_2 and Na_2O and a high negative correlation with TiO_2 and Al_2O_3 , indicating that SiO_2 is found mostly in quartz in the coarser-size fraction and that TiO_2 and Al_2O_3 are concentrated in the finer-size fraction, probably as clay minerals. Cu, Pb, and Zn also had a high

correlation with each other and with Ga and V, and Pb had a high correlation with Ni. These elements were probably elevated in the ore and waste material at the Pecos mine.

TABLE 1. Summary of analytical methods. FAAS=flame atomic absorption spectroscopy. XRF= X-ray fluorescence. ICP-AES= inductively coupled plasma-atomic emission spectrometry. XRD= X-ray diffraction

Area	Number of samples	Type of samples	Particle size fractions	Analytical methods	Reference
Pecos mine and Alamitos Canyon mill, Santa Fe County	6 samples May 1994, 8 samples September 1994	Stream sediments	1-2 mm, 0.5-1 mm, 250 m-0.5 mm, 125-250 μ m, 63-125 μ m, and <63 μ m	FAAS (for Cu, Pb, Zn, Cd, Fe, Mg, and Mn)	McLemore et al. (1993, 1995)
Hillsboro district, Sierra County	5 samples	Waste rock piles from different types of deposits	1-2 mm, 0.5-1 mm, 250 m-0.5 mm, 125-250 μ m, 63-125 μ m, and <63 μ m	FAAS, XRF (Cu, Pb, Zn, As)	Munroe (1999)
Questa molybdenum mine, Taos County	12 samples	Questa waste rock piles, debris flows, and alteration scars	>1 inch, 1-0.75 inch, 0.75-0.5 inch, 0.5-0.187 inch, 0.187-0.0787 inch, and <0.0787 inch (>25 mm, 25-19 mm, 19-12.5 mm, 12.5-4.75 mm, 4.75-2 mm, <2 mm)	paste pH and paste conductivity measurements, Acid-Base-Accounting (ABA) tests, whole rock chemistry by XRF, clay mineralogy using XRD	McLemore et al. (2009a, b, c), Graf (2009), Morkeh and McLemore (2012)
Mockingbird Gap, Salinas Peak, Grandview-Sulphur Canyon, Lake Valley, Tularosa, Orogrande	39 samples	waste rock piles from six mining districts	>8 mesh (~2 mm), 8 to 100 mesh (~2 to 0.150 mm), and <100 mesh (<0.150 mm)	ICP-AES, 40 elements	Herring et al. (1998)

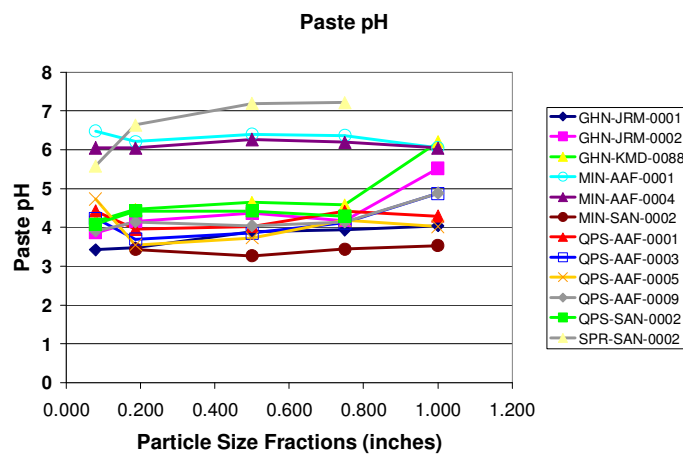
Hillsboro district, Sierra County, New Mexico

Munroe et al. (1999) in a study of waste rock piles from different types of deposits in the Hillsboro district in central New Mexico, found that the <0.25 mm size fraction typically contained the highest Cu, Pb, Zn, and As concentrations. The <0.25 mm size fractions represented <20% of the total sample weight.

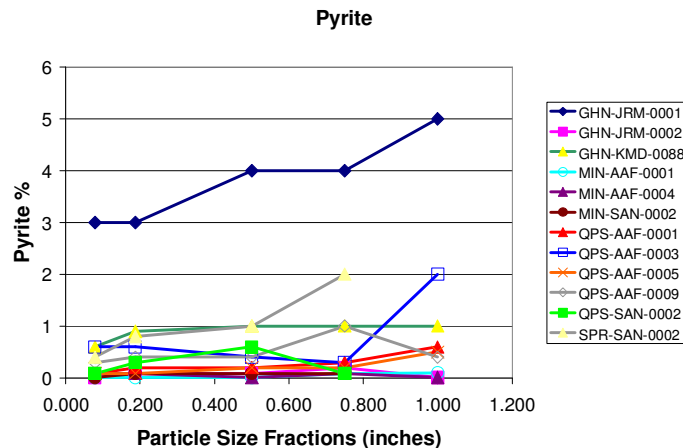
Questa molybdenum mine, Taos County, New Mexico

Morkeh and McLemore (2012) described the differences in geochemistry, mineralogy, texture, and acid potential between different particle size fractions of samples from the Questa rock piles, debris flows, and alteration scars. The weight percentage of fines was less than 17% for all samples. There were differences between the particle size fractions geochemically. The finer-size fractions were more acid producing than the coarser-size fractions. The finer-size fractions had higher net acid producing potential (NAPP) and lower paste pH (Fig. 2A). Conversely, the coarser-size fractions had lower neutralizing potential distribution (NP) (Fig. 3). For some samples, paste pH values decrease from the

coarser-size fraction to the finer-size fraction, but not all samples show a significant decrease. There was not a consistent trend in the chemistry and mineralogy between size fractions for all the samples observed. Al_2O_3 shows little change with different size fractions. For most of the samples, concentrations of feldspar, pyrite (Fig. 2B), Na_2O and K_2O decreased from coarse to fine fractions, while the concentration of FeO , CaO , and SO_4 and total sulfates (gypsum + jarosite) increased with decreasing size fraction for most samples. Silicate dissolution can be inferred from the decrease in feldspar, Na_2O and K_2O from coarse- to fine-size fractions. Similar trends were found by Graf (2008) in the Hansen alteration scar. Collectively, these results are consistent with weathering being more pronounced in the finer-size fraction than the coarser-size fraction. The dissolution of pyrite, calcite, and to a lesser extent some combination of chlorite, illite, feldspars, smectite, and other silicate minerals are the predominant chemical reactions that results in the precipitation of gypsum, jarosite, soluble efflorescent salts, and Fe oxide/hydroxide minerals, mostly in the fine-size fractions, although some authigenic gypsum crystals can be quite large.



A.



B.

Figure 2. (A) Variations of paste pH with different particle size fractions. Generally, the fine-size fractions have lower paste pH values. (B) Variations in pyrite with different size fractions. From Questa rock piles (Morkeh and McLemore, 2012).

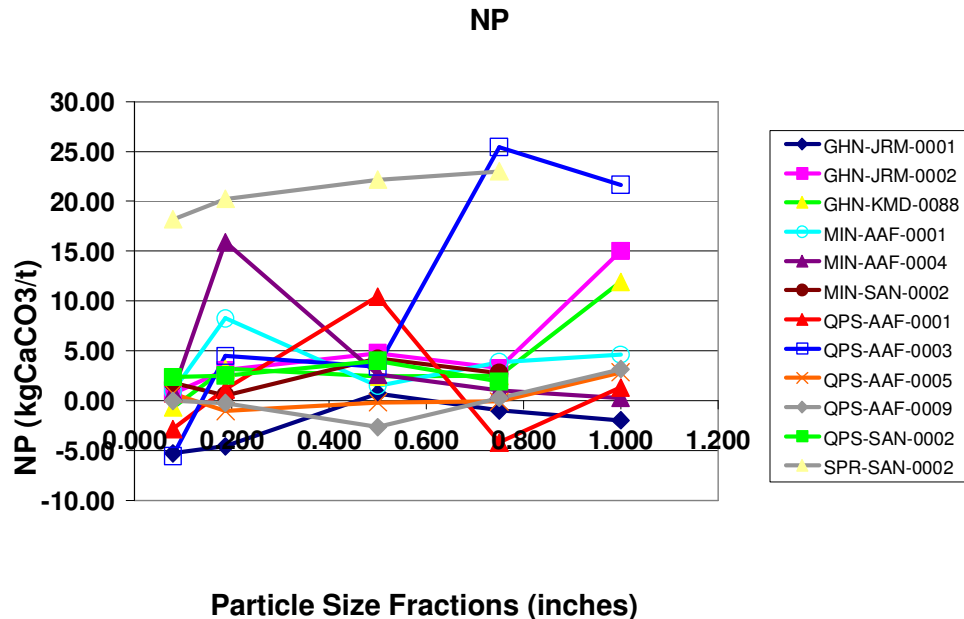


Figure 3. Plot of neutralizing potential distribution (NP) vs. size fraction. the coarser-size fractions had lower neutralizing potential distribution From Questa rock piles (Morkeh and McLemore, 2012).

Graf (2008) found an increase in FeO, CaO, and SO₄ between the coarse- and fine-size fractions in weathered samples from the Hansen alteration scar, east of the Questa mine. He attributed the increase in CaO and SO₄ to the precipitation of gypsum. Silicate dissolution was recognized from coarse- to fine-size particles by the decrease in Na₂O and K₂O, and the large change in total feldspar from coarse- to fine-size fractions (Graf, 2008). The clay mineralogy was consistent between the coarse- and fine-size fractions in these natural geologic materials.

Other mining districts in Socorro, Sierra, and Otero Counties

Herring et al. (1998) found that of the 39 samples analyzed from different host rocks and different types of deposits, about one-half of the samples had the largest concentration of the various elements in the finer-size fractions. For the trace elements, enrichment occurred in the finer-fraction for more than one-half of the samples in all districts for As, Ba, Co, Cr, Cu, La, Li, Mo, Nd, Sc, and V, with slightly lesser enrichments of Ce, Mn, Ni, Pb, Sr, Y, and Zn (Herring et al., 1998). In individual districts, the Mockingbird Gap and Salinas Peak districts had the greatest concentration by at least a factor of 1.5 in the finer fraction for at least half the samples in Ce, Nd, V, and Zn. Goodfortune Creek samples (Salinas Peak district) had the largest concentration in the finer fraction by at least a factor of 1.5 in both samples for As, Ce, Co, La, Mn, Mo, and Nd. Bearden Canyon samples (Salinas Peak district) had the largest concentration in the finer fraction of both samples by at least a factor of 1.5 for Cd, Co, Ga, La, Mn, Mo, Ni, Pb, Sc, V, Y, and Zn. Samples from the Lake Valley district had enrichments for at least half of the samples for As and Cu. Samples from the Tularosa district had similar concentrations in Be and Cr, and samples from the Orogrande district for Cu and Pb. In summary, there is a significant enrichment of many of the trace elements in the finer-size fraction, but not all. The composition appears to be independent of host rock and deposit type.

Discussion

Detailed petrographic examinations of materials forming the rock piles as well as local host rocks provide insights into understanding the geologic, geochemical, pedological and man-influenced

processes that can result in the variations in mineralogy and chemistry within different particle size fractions. The size of the original primary igneous minerals during crystallization, often in a fine-grained groundmass, results in minerals of different sizes that are subsequently liberated from the rock fragments (Fig. 4; McLemore et al., 2008). Some of these minerals, such as biotite and hornblende, are more susceptible to weathering and liberation from the host rock than other, more resistant minerals, such as quartz (Acosta et al., 2011).

Pre-mining hydrothermal alteration and weathering can result in the replacement of larger primary silicate minerals by smaller hydrothermal clay minerals (Fig. 5; Molling, 1968; Graf, 2008; McLemore et al., 2008). These replacement clay minerals can remain in the larger size fractions until liberated during mining and dumping into the rock piles or subsequent physical weathering (Fig. 5). Much of the material forming waste rock piles is actually small rock fragments that contain these minerals (McLemore et al., 2010). In many rock pile samples, the fine-grained soil matrix is weathered, while interiors of rock fragments (even within weathered rock pile material), exhibit little or no signs of weathering (McLemore et al., 2008, 2009a, 2009b, 2010).



Figure 4. Note the different sizes of the minerals within typical lithologies. (A) Sample ROC-VTM-G010 is pink, plagioclase aplite porphyry to porphyritic aplite with large quartz, feldspar, and biotite phenocrysts. (B) Sample ROC-VTM-G005 showing typical porphyritic texture of the cream-colored Goathill Porphyry with a finer-grained matrix. From the Questa mine (McLemore et al., 2009b).

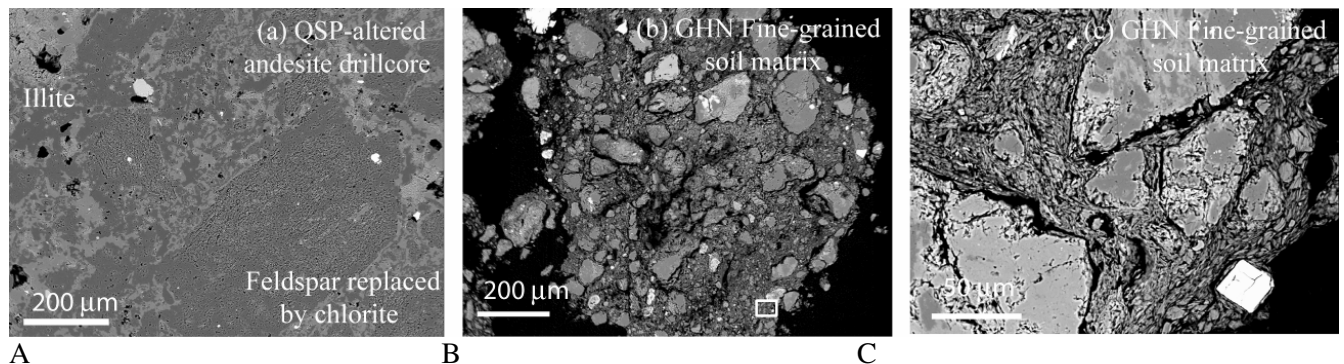


Figure 5. Evidence of primary igneous minerals being replaced by pre-mining, hydrothermal clay minerals (A) Backscatter (BSE) images of QSP-altered andesite drill core (pre-mining alteration), (B)

fine-grained soil matrix samples from GHN rock pile, (C) the magnification of fine-grained soil matrix outlined by the white box in figure 5b. From the Questa mine (McLemore et al., 2009a, 2010).

The mineralized, ore material can be more friable and less cemented, compared to other more resistant, typically silicified material that can form the wall rock in many districts (Herring et al., 1998). This can result in different size fractions within the waste rock pile. Regional fracturing of the pre-mined rock during igneous intrusion and hydrothermal alteration results in materials of different sizes (Ludington et al., 2005). The breaking up of the rock material during blasting, hauling, and dumping during mining also contributes to differences in size fractions (McLemore et al., 2009a, b). Physical (freeze-thaw) and chemical weathering can further produce different size fractions within the rock piles (Fig. 6A; Ludington et al., 2005; Graf, 2008).

Precipitation of weathered minerals, such as gypsum, along fractures and veins, which increase the mineral volume and breaks apart the rock (Fig. 6) and also produces new minerals of different sizes. Some of these precipitated minerals can cement the rock fragments, thereby increasing the particle size. Other minerals, such as pyrite and galena can form rims of less soluble oxides and other minerals that can armor the original crystals and prevent further weathering (Fig. 7; Munroe et al., 1999, 2000; McLemore et al., 2008, 2009a, b).

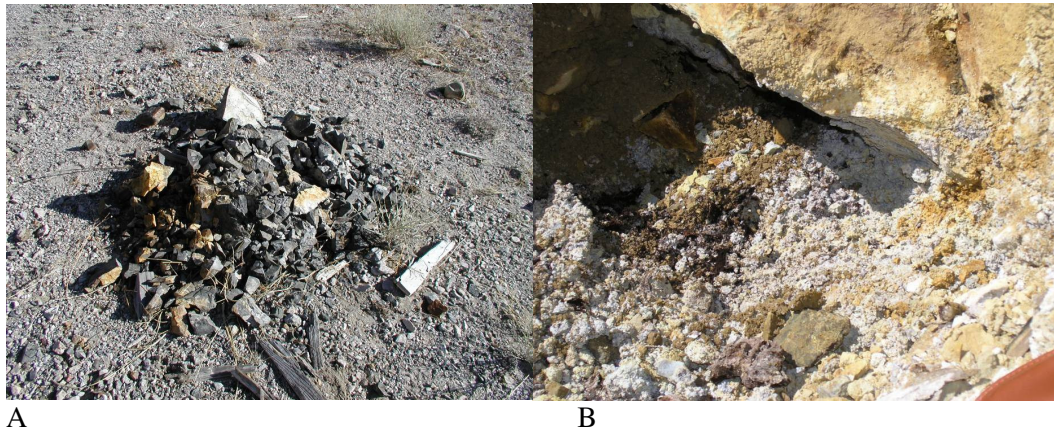


Figure 6. (A) Boulder of andesite that fell apart along veins filled with pyrite, partially altered to jarosite and Fe oxides, gypsum, and calcite. This is a result of physical weathering. (B) Surficial zones of white to yellow-brown soluble salts, gypsum, and jarosite within the Goathill North rock pile at Questa, an example of chemical weathering (McLemore et al., 2008).

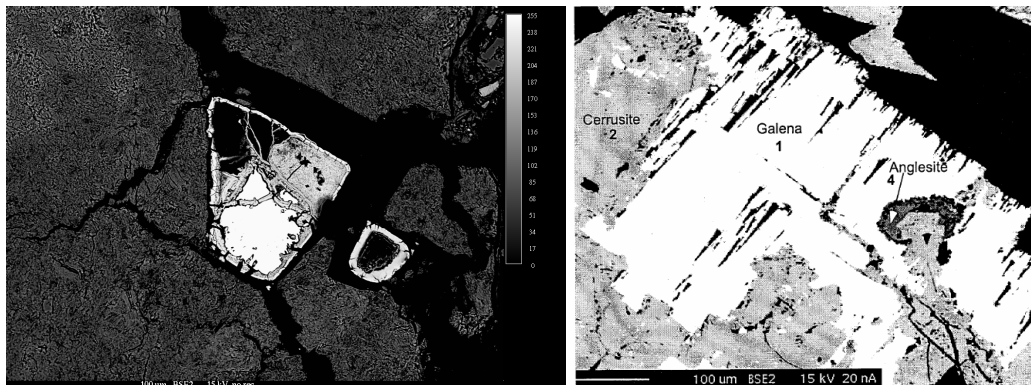


Figure 7. (A) Oxidation of pyrite from Questa rock pile (back-scattered electron microprobe image of sample GHN-KMD-0074-30-02, McLemore et al., 2008). (B) Back-scattered electron microprobe

image of galena replaced and rimmed by cerussite and anglesite from a carbonate-hosted rock pile in the Hillsboro district (Munroe, 1999).

Conclusions

In general, there are consistent results between the four studies. The finer-size fractions are typically the smallest proportion of the sample by weight (generally, <25% in the <2 mm fraction). However, the greatest enrichments of trace elements generally occur in the finer-size portion of the sample.

In the Questa samples, feldspar, quartz, and pyrite are generally higher in the coarser-size fraction. Total clay minerals, gypsum, and jarosite are higher in the finer-size fraction. Paste pH values decrease from the coarser-size fraction to the finer-size fraction, but not all samples show a significant decrease. The coarser-size fractions are less acid generating than finer-size fractions. Na₂O and S increase in the coarser-size fraction, whereas SO₄ decreases in the coarser-size fraction. Al₂O₃ shows little change with different size fractions.

Collectively, these results are consistent with weathering being more pronounced in the finer-size fraction than the coarser-size fraction. The dissolution of pyrite, calcite, and to a lesser extent some combination of chlorite, illite, feldspars, smectite, and other silicate minerals are the predominant chemical reactions that result in the precipitation of gypsum, jarosite, soluble efflorescent salts, and Fe oxide/hydroxide minerals. These precipitates are mostly in the finer-size fractions, although some authigenic gypsum crystals can be quite large.

No single geologic, geochemical, pedological or man-influenced process is responsible for the differences in composition between particle size fractions. The effects of primary igneous crystallization, pre-mining hydrothermal alteration and weathering, and post-mining blasting, hauling, dumping, and emplacement into the rock pile and subsequent weathering affect the composition of each size fraction. This emphasizes the need to determine not only the composition of the different size fractions, but also perform detailed mineralogy and petrology investigations to understand the processes involved in controlling the compositional differences between size fractions. Although the results are generally consistent, there is some variation between samples and it is recommended that composition of different particle sizes be examined at all environmental sites, especially mine sites.

The importance of understanding the effect of composition on particle size can be used to 1) help plan and assess reclamation procedures, 2) compare trace-element concentrations in mined versus undisturbed areas, 3) determine background concentrations, 4) determine the best size fractions for prediction tests, such as humidity cell tests, and 5) provide background data that can assist with the planning of future mining operations. Benefits to the public include the assessment of changes in environmental parameters of pre-, post-, and abandoned-mined lands, including changes where mining and reclamation activity have improved the quality of those environmental parameters.

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References

- Acosta, J.A., Martinez-Martinez, S., Faz, A. and J. M. Arocena, J.M., 2011, Accumulations of major and trace elements in particle size fractions of soils on eight different parent materials: *Geoderma*, v. 161(1-2), p. 30-42.
- Brandvold, L.A. and McLemore, V.T., 1998, A study of the analytical variation of sampling and analysis of stream-sediments from areas contaminated by mining and milling: *Journal of Geochemical Exploration*, v. 64, p. 185-196.
- Dinelli, E., Tateo, F., and Summa, V., 2007, Geochemical and mineralogical proxies for grain size in mudstones and siltstones from the Pleistocene and Holocene of the Po alluvial plain, Italy; in Aibas, J., Critelli, S., and Johnson, M.J., eds., *Sedimentary province and petrogenesis: Perspectives from petrography and geochemistry*: Geological Society of America, Special Paper 420, p. 25-36.
- Dultz, S., 2002, Effects of parent material and weathering on feldspar content in different particle size fractions from forest soils in NW Germany: *Geoderma*, v. 106, p. 63-81.
- 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, 193 p., <http://geoinfo.nmt.edu/staff/mclemore/Molycorppapers.htm>, accessed April 28, 2008.
- Harley, G.T., 1934, The geology and mineral resources of Sierra County, New Mexico; New Mexico Bureau of Mines and Mineral Resources, Bulletin 10, 220 p.
- Hedlund, D.C., 1985, Economic geology of some selected mines in the Hillsboro and San Lorenzo quadrangles, Grant and Sierra Counties, New Mexico: U.S. Geologic Survey, Open-file Report 85-456, 76 p.
- Herring, J.R., Marsh, S.P., and McLemore, V.T., 1998, Major and trace element concentrations and correlations in mine dump samples from mining districts in Sierra, Socorro, and Otero counties, south-central New Mexico—Mockingbird Gap, Lava Gap, Salinas Peak, Goodfortune Creek, Bearden Canyon, and Sulfur Canyon mining districts of the northern San Andres Mountains, Sierra and Socorro County; Lake Valley mining district of Sierra County; and Tularosa and Orogrande mining districts of Otero County: U.S. Geological Survey Open-File Report 98-486, 21 p.
- Lapakko, K., 2003, Solid phase characterization for metal mine waste drainage quality prediction: Preprint 03-093, 8 p.
- Lapakko, K.A., Haub, J., and Antonson, D.A., 1998, Effect of dissolution time and particle size on kinetic test results: Society for Mining, Metallurgy, and Exploration, SME, Littleton, CO, preprint 98-114.
- Lindgren, W., Graton, L. C., and Gordon, C. H., 1910, The ore deposits of New Mexico: U.S. Geological Survey, Professional Paper 68, 361 p.
- Lovering, T.G. and Heyl, A.V., 1989, Mineral belts in western Sierra County, New Mexico, suggested by mining districts, geology, and geochemical anomalies: U.S. Geological Survey, Bulletin 1876, 58 p., <http://pubs.er.usgs.gov/usgspubs/b/b1876>.
- Ludington, S., Plumlee, G.S., Caine, J.S., Bove, D., Holloway, J.M., and Livo, K.E., 2005, Questa Baseline and Pre-Mining Ground-Water Quality Investigation. 10. Geologic influences on ground and surface waters in the lower Red River watershed, New Mexico. U.S. Geological Survey Scientific Investigations Report 2004-5245, <http://pubs.usgs.gov/sir/2004/5245/>, accessed 11/8/08.
- McLemore, V.T., 2001, Silver and gold resources in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Resource Map 21.
- McLemore, V.T., 2009, Geologic setting and mining history of the Questa mine, Taos County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Report 515, 29 p., <http://geoinfo.nmt.edu/publications/openfile/details.cfm?Volume=515>
- McLemore, V. T., Brandvold, L. A., and Brandvold D. K., 1993, A reconnaissance study of mercury and base metal concentrations in water, stream- and lake-sediment samples along the Pecos River in eastern New Mexico: New Mexico Geological Society, Guidebook 44, p. 339-351.
- McLemore, V.T., Brandvold, L.A., Hossain, A.M., Pease, T.C., 1995, The effect of particle size distribution on the geochemistry of stream sediments from the upper Pecos River, San Miguel County, New Mexico: New Mexico Geological Society, Guidebook 46, p. 323–329.
- McLemore, V.T., Dickens, A., 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., 2008, Characterization of Goathill North Rock Pile: New Mexico Bureau of Geology and Mineral Resources, Open-file report 523, <http://geoinfo.nmt.edu/publications/openfile/details.cfm?Volume=523>
- McLemore, V.T., Dunbar, N., Tachie-Menson, S., and Donahue, K., 2010, The Effect of Weathering on the Acid-Producing Potential of the Goathill North Rock Pile, Questa mine, NM: CRC Press, Taylor and Francis Group, London, Tailings and Mine Waste '10, p. 213-227.
- McLemore, V., Heizler, L., Donahue, K., and Dunbar, N., 2009a, Characterization of Weathering of Mine Rock Piles: Example from the Questa Mine, New Mexico, USA: Securing the Future and 8th ICARD, June 23-26 2009, Skelleftea, Sweden, conference proceedings, 10 p., http://www.proceedings-stfandicard-2009.com/pdfer/Virginia_McLemore_P_T2_Characterization-of-weathering-of-mine-rock-piles-example-from-the-Questa-mine-New-Mexico-USA.pdf
- McLemore, V.T., Munroe, E.A., Heizler, M.T. and McKee, C., 1999, Geochemistry of the Copper Flat porphyry and associated deposits in the Hillsboro mining district, Sierra County, New Mexico, USA: Journal of Geochemical Exploration, v. 66, p. 167-189.
- McLemore, V.T., Munroe, E.A., Heizler, M.T. and McKee, C., 2000, Geology and evolution of the Copper Flat Porphyry Copper and associated mineral deposits in the Hillsboro mining district, Sierra County, New Mexico; in Cluer, J. K., Price, J. G., Struhsacker, E. M., Hardyman, R. F. and Morris, C. L. eds., Geology and Ore Deposits 2000, The Great Basin and Beyond: Geological Society of Nevada, Symposium Proceedings, p. 643-659.
- McLemore, V.T., Sweeney, D., and Donahue, K., 2009b, Lithologic atlas: New Mexico Bureau of Geology and Mineral Resources, Open-file Report 516, 73 p., <http://geoinfo.nmt.edu/publications/openfile/details.cfm?Volume=516>
- McLemore, V., Sweeney, D., Dunbar, N., Heizler, L. and Phillips, E., 2009c, Determining quantitative mineralogy using a combination of petrographic techniques, whole rock chemistry, and MODAN: Society of Mining, Metallurgy and Exploration Annual Convention, Denver, Feb 2009, Preprint 09-20, 19 p., http://geoinfo.nmt.edu/staff/mclemore/documents/09-020_19.pdf
- Molling, P.A., 1989, Applications of the reaction progress variable to hydrothermal alteration associated with the deposition of the Questa molybdenite deposit, NM: PhD dissertation, Johns Hopkins University, 227 p.
- Morkeh, J. and McLemore, V.T., 2012, The effect of particle size fractions on chemistry, mineralogy, and acid potential of the Questa rock piles, Taos County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Report 545, 96 p., http://geoinfo.nmt.edu/publications/openfile/downloads/OFR500-599/526-550/545/ofr_545.pdf
- Munroe, E.A., 1999, Geology and geochemistry of waste rock piles in the Hillsboro mining district, Sierra County, New Mexico (M. S. thesis): New Mexico Institute of Mining and Technology, Socorro, 144 p., http://www.ees.nmt.edu/outside/alumni/papers/1999t_munroe_ea.pdf
- Munroe, E.A., McLemore, V.T., and Kyle, P., 1999, Waste rock pile characterization, heterogeneity and geochemical anomalies in the Hillsboro mining district, Sierra County, New Mexico: Journal of Geochemical Exploration, v. 67, p. 391-405
- Munroe, E.A., McLemore, V.T., and Dunbar, N.W., 2000, Mine waste rock pile geochemistry and mineralogy in southwestern New Mexico, USA; in ICARD 2000—Proceedings from the 5th international conference on acid rock drainage: Society for Mining, Metallurgy, and Exploration, Inc., Littleton, Colo., p. 1327-1336.
- Popp, C.J., Brandvold, D.K., Kirk, K., Brandvold, L.A., McLemore, V.T., Hansen, S., Radtke, R., and Kyle, P. R., 1996, Reconnaissance investigation of trace metal sources, sinks, and transport in the upper Pecos River Basin, New Mexico: U.S. Bureau of Reclamation, Report No. 3-FC-4D-13830, 224 p.
- Strömberg, B. and Banwart, S.A., 1999, Experimental study of acidity-consuming processes in mining waste rock: some influences of mineralogy and particle size: Applied Geochemistry, v. 14, p. 1-16.
- Taboada, T., Cortizas, A.M., García, C., García-Rodeja, E., 2006, Particle-size fractionation of titanium and zirconium during weathering and pedogenesis of granitic rocks in NW Spain: Geroforma, v. 131, p. 218-236.