

DRA-46. SLAKE DURABILITY AND POINT LOAD INDICES OF QUESTA MINE ROCK FRAGMENTS

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1. STATEMENT OF THE PROBLEM

What are the point load and slake durability indices of Questa rock-pile and analog materials and how do these parameters relate to weathering and alteration? Point load strength and slake durability indices can provide a measure of the strength and durability of rock fragments and are related to the intensity of weathering.

2. PREVIOUS WORK

Slake durability and point load strength indices are two important geotechnical parameters that can be used in characterizing the strength of rock fragments and their durability to weathering. Dick and Shakoor (1995) explained that durability is an important parameter that affects the stability of natural and man-made slopes consisting of mudrocks. Dhakal et al. (2002) stated that, the slaking behavior of pyroclastic (similar to the Amalia Tuff) and sedimentary rocks can play a major role in the slope failure. Nevertheless, very few studies of rock piles evaluate point load, slake durability tests and understand the relationships with mineralogy, chemistry and other geotechnical parameters. Actual slake durability and point load indices from researchers such as Quine (1993) reported point load indices for some rock-pile samples collected in Nevada that ranged from 2.9 to 4.6 MPa, while the slake durability indices ranged from 88 to 99% with an additional single value of 6%. Samples from the Eskihisar lignite mine in Turkey (Gökçeoglu et al., 2000) had slake durability indices ranging from 88.7 to 96.8%, and rock-pile material from a marble mine in India had slake durability indices ranging from 89.9 to 97.0% (Maharana, 2005).

3. TECHNICAL APPROACH

Sampling

Details of the sampling procedures are found in Viterbo (2007), Ayakwah et al. (2009), DRA-0, and project SOPs. Samples consist of representative rock pieces, each weighing between 40 and 60 g (approximately 4-10 cm in dimension). Samples were collected specifically for examining relationships between slake durability and point load indices and mineralogy, chemistry, lithology, geotechnical parameters, and weathering/alteration. Several different types of samples were collected:

- Rock fragments from rock-pile material that includes mixtures of different lithologies and alteration assemblages
 - Samples collected from the surface and from test pits throughout the rock piles
 - Samples of the rock pile material collected from trenches in Goathill North (GHN) rock pile (5 ft channel or composite of selected layers)
- Outcrop samples of unweathered (or least weathered) igneous rocks representative of the mined rock (overburden) (includes all predominant lithologies and alteration assemblages at various hydrothermal alteration and weathering intensities)
 - andesite
 - quartz latite
 - rhyolite tuff (Amalia Tuff)
 - aplite, granitic porphyry

- miscellaneous dike, flow, and tuffaceous rocks
- alteration scars
- Soil profiles of colluvium/weathered bedrock, alteration scar, and debris flows
- Sections of drill-core samples of the mined rock (overburden) and ore deposit before mining.

Different sampling strategies were employed based upon the purpose of each sampling task. Typically, at each site, a select, grab, or bulk sample of rock or rock-pile material was collected for petrographic study and geochemical and geotechnical analyses. The samples of analogs and drill cores consisted of grab samples of two or more pieces (typically 3-8 cm in diameter). These samples are more homogeneous than rock-pile samples in that they are composed of one lithology and alteration assemblage, whereas the rock-pile material typically consists of multiple lithologies and/or alteration assemblage. A portion of the collected sample was crushed and pulverized for geochemical analysis. Thin sections were made of another portion of selected rock samples for petrographic analysis (including estimated modal mineralogical analysis). Another portion was used for the geotechnical testing. DRA-0 includes a summary of samples and sample preparation for the various analyses.

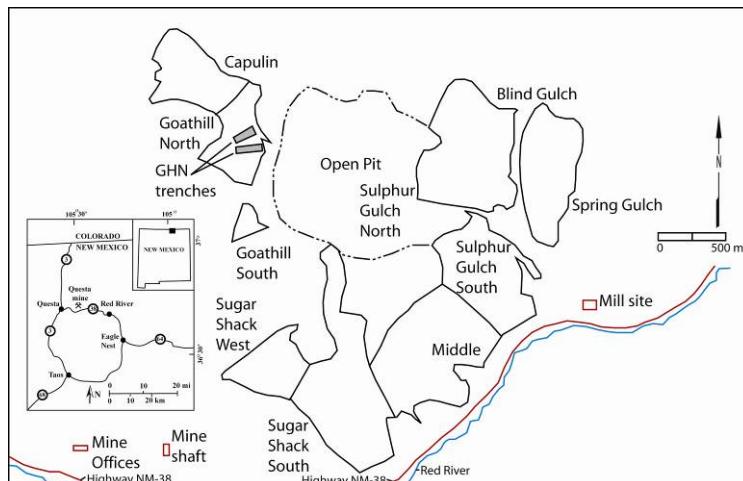


FIGURE 1. Rock piles and other mine features, Questa mine, New Mexico.

Slake Durability Index

The slake durability test was developed by Franklin and Chandra (1972), recommended by the International Society for Rock Mechanics (ISRM, 1979) and standardized by the American Society for Testing and Materials (ASTM, 2001) (SOP 76). The purpose of the test is to evaluate the influence of alteration on rocks by measuring their resistance to deterioration and breakage when subjected to simulated wetting and drying cycles. The slake durability index (ID_2) is a measure of durability and provides quantitative information on the mechanical behavior of rocks according to the amount of clay and other secondary minerals produced in them due to exposure to climatic conditions (Fookes et al., 1971). The ID_2 is obtained from:

$$ID_2 = \frac{W_A - W_D}{W_B - W_D} \times 100 \quad (1)$$

where W_B is the mass of drum plus oven-dried sample before the first cycle, W_A is the mass of drum plus oven-dried sample retained after the second cycle, and W_D is the mass of drum. All samples are classified according to the classification index in Table 1. Note that each sample in

the slake durability testing is made of 10 pieces of rock each weighing 40 to 60 g that were collected from a specific location.

TABLE 1. Slake durability index classification (Franklin and Chandra, 1972).

ID ₂ (%)	Durability classification
0 – 25	Very low
25 – 50	Low
50 – 75	Medium
75 – 90	High
90 – 95	Very high
95 – 100	Extremely high

Point Load Index

The point load test is a simple test for estimating rock strength (SOP 77). The equipment consists of a loading frame that measures the force required to split the sample and a system for measuring the distance between the two contact loading points. The point load test can be performed on samples with different shapes, both cylindrical (core) and irregular shapes. The point load strength index (Is50) corresponding to a specimen of 0.05 m in diameter, is calculated using (ISRM, 1985):

$$Is50 = \frac{P}{D_e^2} \times F \quad (2)$$

where P is the peak load, D_e is the equivalent core diameter, and F is a size correction factor that is equal to $(D_e/0.050)^{0.45}$ in which D_e is in m. All samples are classified according to the classification index in Table 2.

TABLE 2. Point load strength index classification (Broch and Franklin, 1972).

Is50 (MPa)	Strength classification
< 0.03	Extremely low
0.03 – 0.1	Very low
0.1 – 0.3	Low
0.3 – 1.0	Medium
1.0 – 3.0	High
3.0 – 10	Very high
> 10	Extremely high

Slake durability and point load strength tests were performed on rock samples from the rock piles and analogs, and cores of the mined rock, drilled before open-pit mining began. The samples from drill cores are assumed to represent unweathered rock-pile material. Note that each sample in the point load testing is made of 5 to 20 pieces of rock collected at a specific location. The point load index of a sample was calculated using the procedure explained in Appendix 1.

4. CONCEPTUAL MODEL

Slake durability and point load indices are measures of the strength of rock material. The geologic conceptual model and summary of weathering for GHN is in Appendix 2 and DRA-6 and 27.

5. STATUS OF COMPONENT INVESTIGATION

Viterbo (2007), Viterbo et al. (2007), Gutierrez et al. (2008), and McLemore et al. (2008a) examined samples from GHN rock pile for slake durability and point load tests and their results are summarized in this DRA, along with new data. Ayakwah et al. (2009) expand upon this work by examining the relationships of slake durability and point load indices with geotechnical parameters, mineralogy, chemistry, and weathering for samples other than GHN, some of which are summarized in this DRA. Samples tested include a wide range of lithologies, hydrothermal alteration intensities, and weathering intensities found at Questa. Appendix 3 include summary descriptive statistics of the point load and slake durability data for Questa materials. Summary descriptive statistics are in Tables 3 and 4, also GHN rock pile, all rock piles, weathered/unweathered andesite, rhyolite (Amalia Tuff), and aplite, and analog (alteration scar, debris flow) samples statistics are in Tables 3-1 to 3-6 (Appendix 3).

TABLE 3. Summary descriptive statistics of the strength classification for all samples. Samples from Southwest Hansen (SWH) and Hansen (HAS) alteration scar were too weak to perform point load test, hence those point load test results are not included in this table. This was probably a result of highly fractured nature of the samples collected from these areas.

Location	Statistics	Point Load Strength Index
All rock piles (GHN, Sugar Shack South, Sugar Shack West, Middle, Spring Gulch)	No. of Samples	59
	Mean (MPa)	3.8
	Standard Deviation (MPa)	1.7
	Minimum (MPa)	0.6
	Maximum (MPa)	8.2
	Coefficient of Variation (%)	44.71
All unweathered (drill core) andesite samples	No. of Samples	15
	Mean (MPa)	3.7
	Standard Deviation (MPa)	1.7
	Minimum (MPa)	1.3
	Maximum (MPa)	6.9
	Coefficient of Variation (%)	45.9
All weathered and unweathered (drill core and outcrop) rhyolite (Amalia) and aplite samples	No. of Samples	5
	Mean (MPa)	3.3
	Standard Deviation (MPa)	1.1
	Minimum (MPa)	1.8
	Maximum (MPa)	4.8
	Coefficient of Variation (%)	33.3
All unweathered (drill core) rhyolite (Amalia)	No. of Samples	3
	Mean (MPa)	2.6
	Standard Deviation (MPa)	0.7
	Minimum (MPa)	1.8
	Maximum (MPa)	3.1
	Coefficient of Variation (%)	33.3
Debris Flow	No. of Samples	12
	Mean (MPa)	4.0
	Standard Deviation (MPa)	1.0
	Minimum (MPa)	2.6

Location	Statistics	Point Load Strength Index
	Maximum (MPa)	6.0
	Coefficient of Variation (%)	25.0
Alteration Scars (Questa Pit)	No. of Samples	4
	Mean (MPa)	2.8
	Standard Deviation (MPa)	0.8
	Minimum (MPa)	1.7
	Maximum (MPa)	3.8
	Coefficient of Variation (%)	28.6

TABLE 4. Summary descriptive statistics of the durability classification for all samples.

Location	Statistics	Slake Durability Index
All rock piles (GHN, Sugar Shack South, Sugar Shack West, Middle, Spring Gulch)	No. of Samples	120
	Mean (%)	96.6
	Standard Deviation (%)	3.1
	Minimum (%)	80.9
	Maximum (%)	99.5
	Coefficient of Variation (%)	3.42
All weathered (out crop) and unweathered (drill core) andesite samples	No. of Samples	27
	Mean (%)	95.3
	Standard Deviation (%)	4.2
	Minimum (%)	83.7
	Maximum (%)	99.6
	Coefficient of Variation (%)	4.4
All weathered and unweathered (drill core) andesite samples	No. of Samples	22
	Mean (%)	95.4
	Standard Deviation (%)	4.2
	Minimum (%)	83.7
	Maximum (%)	99.6
	Coefficient of Variation (%)	4.4
All weathered (out crop) and unweathered (drill core) rhyolite (Amalia) and aplite samples	No. of Samples	18
	Mean (%)	95.5
	Standard Deviation (%)	2.8
	Minimum (%)	88.9
	Maximum (%)	99.5
	Coefficient of Variation (%)	2.9
All weathered and unweathered (drill core) rhyolite (Amalia) and aplite samples	No. of Samples	3
	Mean (%)	92.98
	Standard Deviation (%)	3.6
	Minimum (%)	88.9
	Maximum (%)	95.8
	Coefficient of Variation (%)	3.9
Debris Flow	No. of Samples	18
	Mean (%)	98.4

	Standard Deviation (%)	0.9
	Minimum (%)	96.1
	Maximum (%)	99.6
	Coefficient of Variation (%)	0.9
Alteration Scars (Questa Pit, Hason, Goat Hill, Straight Creek scars)	No. of Samples	24
	Mean (%)	89.2
	Standard Deviation (%)	9.2
	Minimum (%)	64.5
	Maximum (%)	98.5
	Coefficient of Variation (%)	10.3

6. RELIABILITY ANALYSIS

Samples collected are complete, comparable, and representative of the defined population at the defined scale. The sampling and analysis plans for each segment of the field program and the control of accuracy and precision as defined in the SOPs, provides a large high-quality set of observations and measurements that are adequate to support the interpretations and conclusions of the various technical studies documented in this DRA. It is assumed that the large rock fragments (40 to 60 g, approximately 4-10 cm in size) tested have similar strength as the small rock fragments within the various rock piles and analog sites. This has not been investigated and therefore is a source of uncertainty.

7. CURRENT CONCLUSIONS OF THE COMPONENT

The slake durability indices from GHN are high to extremely high according to the slake durability index classification (Franklin and Chandra, 1972) and the point load indices are medium to very high according to the point load strength index classification (Broch and Franklin, 1972). Samples from the GHN rock pile are similar in slake durability and point load indices regardless of geologic layer and location within the rock pile, except that some, but not all samples located in the outer, weathered edge of the rock pile (units C and I) are weaker and have lower slake durability and point load indices (Fig. 5). Even though these rock fragments have been subjected to hydrothermal alteration, which produced clay mineral contents as high as 30%, these rocks are still quite strong, because the clay minerals replaced primary igneous minerals in the fragments during hydrothermal alteration (Fig. 2-4).

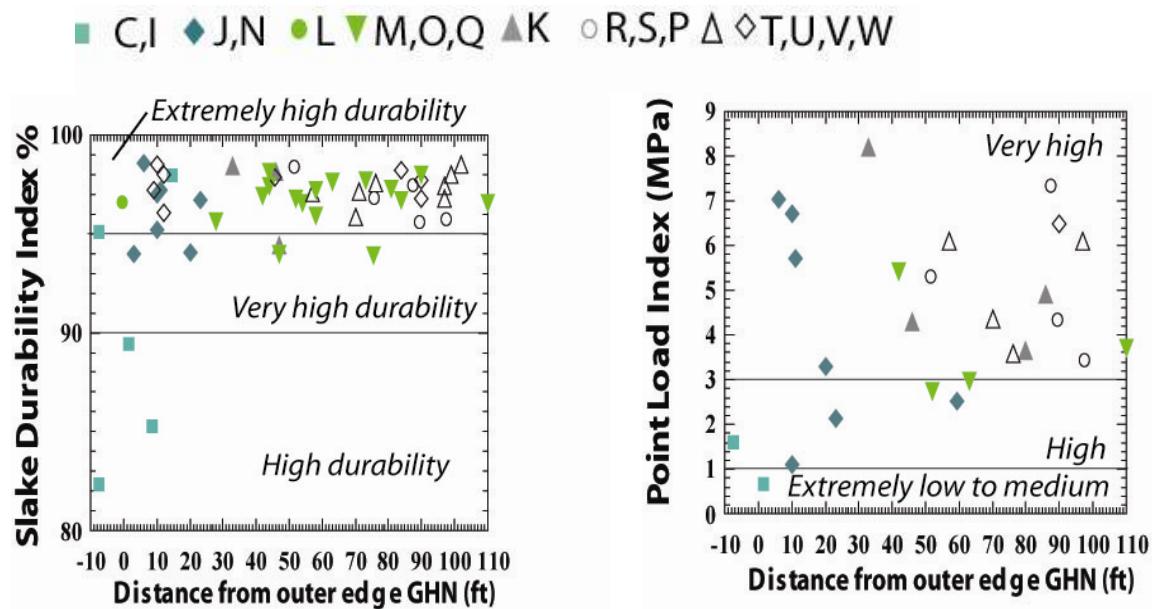


FIGURE 2. Scatter plot of Slake Durability Index and Point Load Index vs. distance from outer edge of GHN rock pile. See Appendix 2 for geologic model of the GHN rock pile.

The slake durability indices from the various Questa rock piles range from 80.9 to 99.5 % and the point load strength indices range from 0.6 to 8.2 MPa (Tables 3, 4, Figs. 3, 4). Samples from Sugar Shack South and Spring Gulch rock piles have a lower average of point load index than the other rock piles; more samples from these rock piles are needed to determine if this is significant.

The slake durability values for samples of andesite and rhyolite (Amalia Tuff) range from 85.5 to 99.6 and 88.9 to 97.5%, respectively, with all samples classified as having high to extremely high durability (Table 1). There is no significant difference in slake durability between different lithologies. The point load index values for these samples range from 1.3 to 6.9 MPa, with all samples classified with high and very high strength (Table 2). The rhyolite samples have slightly lower point load indices.

The slake durability and point load test results statistically indicate that the range of values obtained for samples from the debris flows (average slake durability index of 98.4% and point load index of 4.0 MPa) and the alteration scar samples (average slake durability index of 89.2% and point load index of 2.8 MPa) are similar to the range in values of rock-pile samples (Tables 3, 4, Figs. 3, 4). The debris flows and alteration scars represent the more weathered material that occurred over thousands to millions of years (DRA-19, 20).

Some weathered samples from the edge of GHN, other Questa rock piles, and analog materials show lower slake durability and point load indices than unweathered material, but not all weathered samples have lower slake durability and point load indices. Some samples with low paste pH, but not all, from the edge of GHN, other Questa rock piles, and analog materials show lower slake durability and point load indices (Fig. 5). Paste pH is an indication of weathering, with lower paste pH suggesting more weathered material (Appendix 2; McLemore et al., 2008a). Some weathered samples as indicated by higher SWI, but not all, from the edge of GHN, other Questa rock piles, and analog materials show lower slake durability and point load indices (Fig. 6; Appendix 2). There is no significant correlation between the sum of gypsum and

jarosite and slake durability and point load indices (Fig. 7); although more weathered samples tend to have higher concentrations of gypsum and jarosite (McLemore et al., 2008a). However, after 25-40 years of weathering, the majority of the rock fragments within the rock piles still present high strength.

There are no strong correlations between point load and slake durability indices with friction angle of the material tested (Fig. 8). The friction angle of the fine-grained soil matrix of samples collected along with the rock fragments tested for slake durability and point load indices was obtained using a 2-inch laboratory shear box (Gutierrez et al., 2008). Shear tests were conducted on the air-dried samples.

Questa rock pile samples have high durability and strength even after having undergone hydrothermal alteration and blasting prior to deposition and after potential exposure to weathering for 25-40 years. Collectively, these results suggest that future weathering (<100 years) will not substantially decrease the strength indices of the rock piles with time.

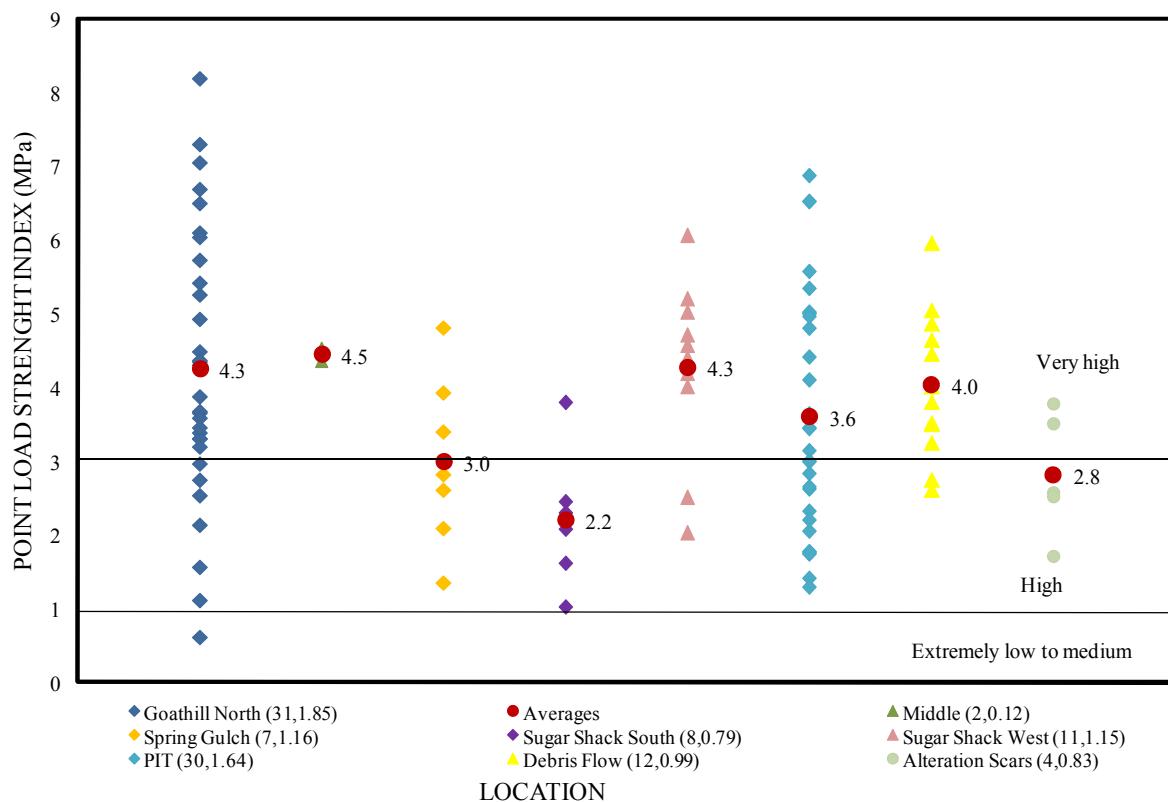


FIGURE 3. Point load strength index values for the rock piles, alteration scars and debris flows. The average point load strength index for each location is shown with a red circle. The number of samples for each location and the standard deviation are shown in parentheses. PIT samples are unweathered drill core samples of andesite and rhyolite (Amalia Tuff) of various hydrothermal alteration intensities. See Figure 1.2 for location of rock piles. See Figures 1.2 and 1.3 for location of trenches and geologic units in GHN where samples were obtained. Appendix B summarizes the location and description of these samples.

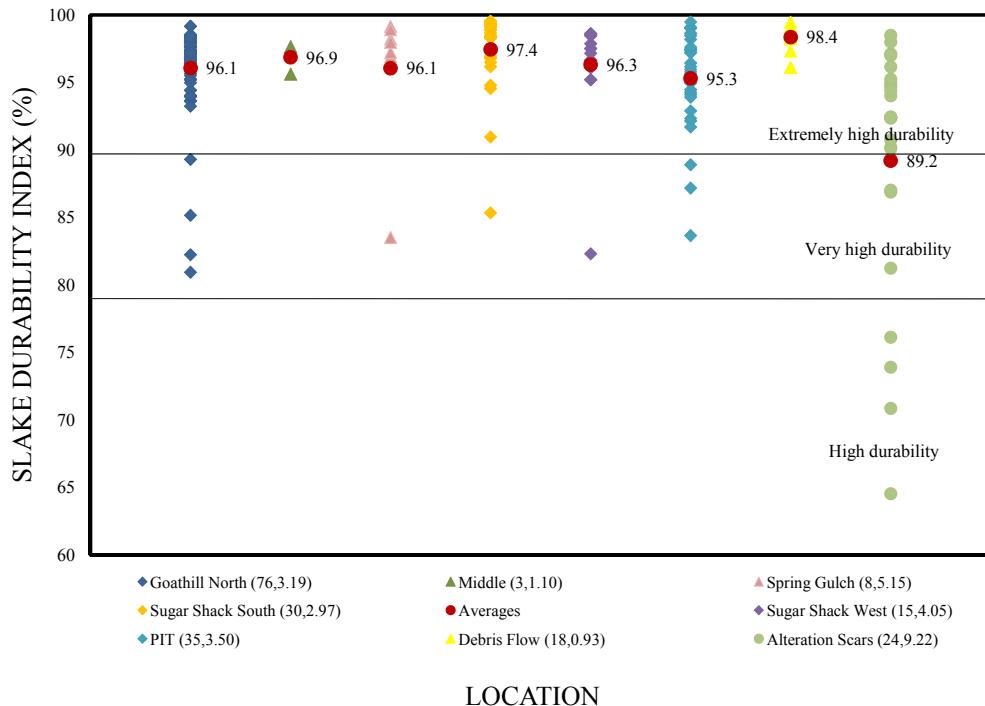


FIGURE 4. Slake durability index values for the rock piles, alteration scars, and debris flows. The average slake durability index for each location is shown with a red circle. The number of samples and the standard deviation for each location are shown in parentheses. PIT samples are unweathered drill core samples of andesite and rhyolite (Amalia Tuff) of various hydrothermal alteration intensities. See Figures 1.2. and 1.3 for location of rock piles and location of trenches and geologic units in GHN where samples were obtained. Appendix B summarizes the location and description of these samples.

■ C,I ▲ J,N ● L▲ M,O,Q▲ K ○ R,S,PΔ T,U,V,W● Other rockpiles ■ Scars highly weathered ■ outcrop highly weathered
 ▶ Amalia & core ◆ Scars mod weathered ▽ Andesite & core ● Scars weathered ▷ outcrop fresh ● Intrusive
 ■ Colluvium & Debris flow ◇ Rubble and traffic ▲ outcrop slightly weathered □ Core Amalia

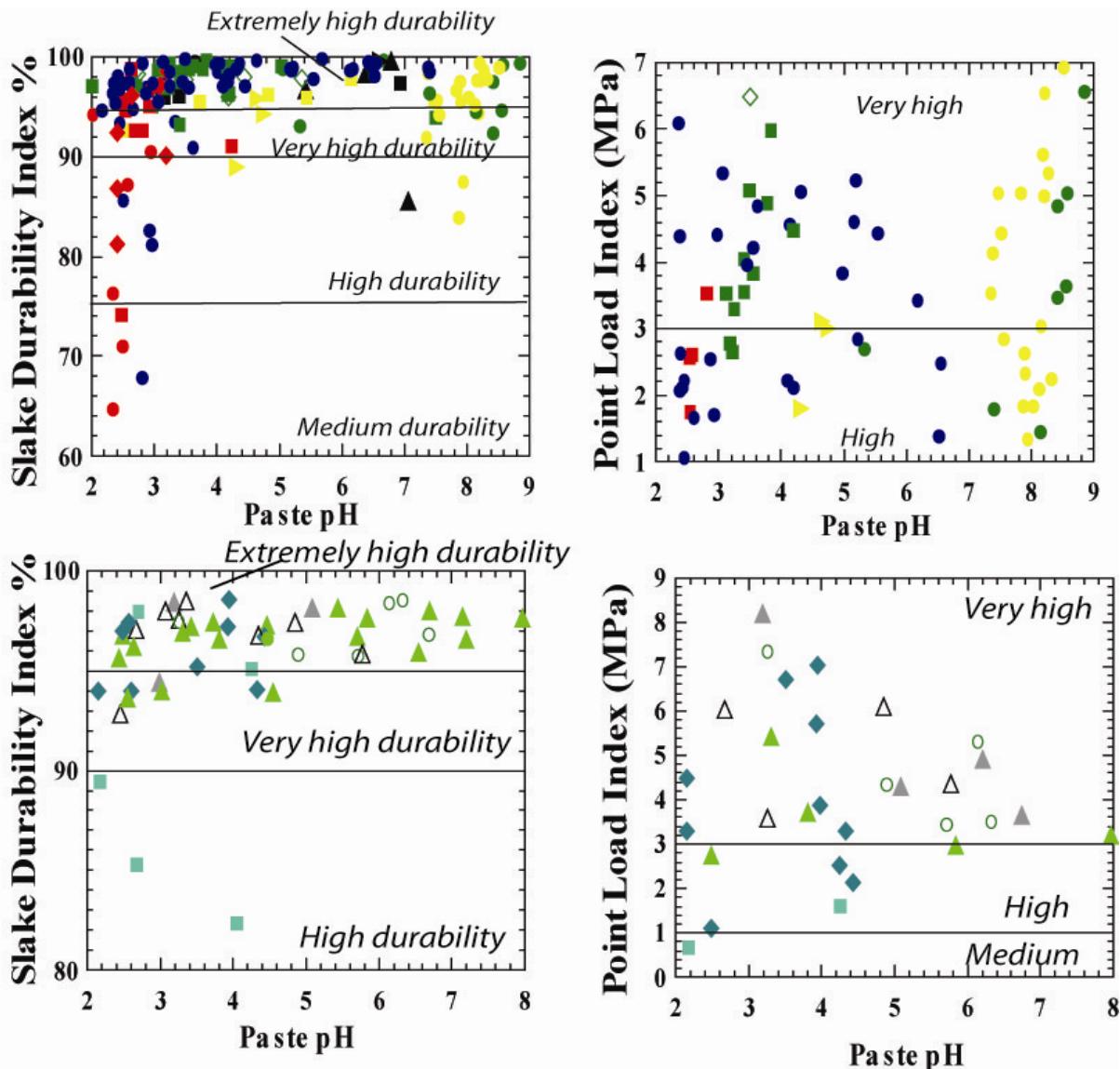


FIGURE 5. Variation in slake index, point load index and paste pH of the Questa rock materials. Some samples with low paste pH, but not all, from the edge of GHN, other Questa rock piles, and analog materials show lower slake durability and point load indices. Paste pH is an indication of weathering, with lower paste pH suggesting more weathered material (McLemore et al., 2008a). The upper part of the figure is for the all the other rock pile location and the analogs except the GHN whereas the lower part is GHN.

■ C,I ♦ J,N ● L▲ M,O,Q▲ K ○ R,S,PΔ T,U,V,W● Other rockpiles ■ Scars highly weathered■outcrop highly weathered
 ▶Amalia & core ◆Scars mod weathered □Andesite & core● Scars weathered▶outcrop fresh ●Intrusive
 ■Colluvium & Debris flow ◇Rubble and traffic ▲outcrop slightly weathered □Core Amalia

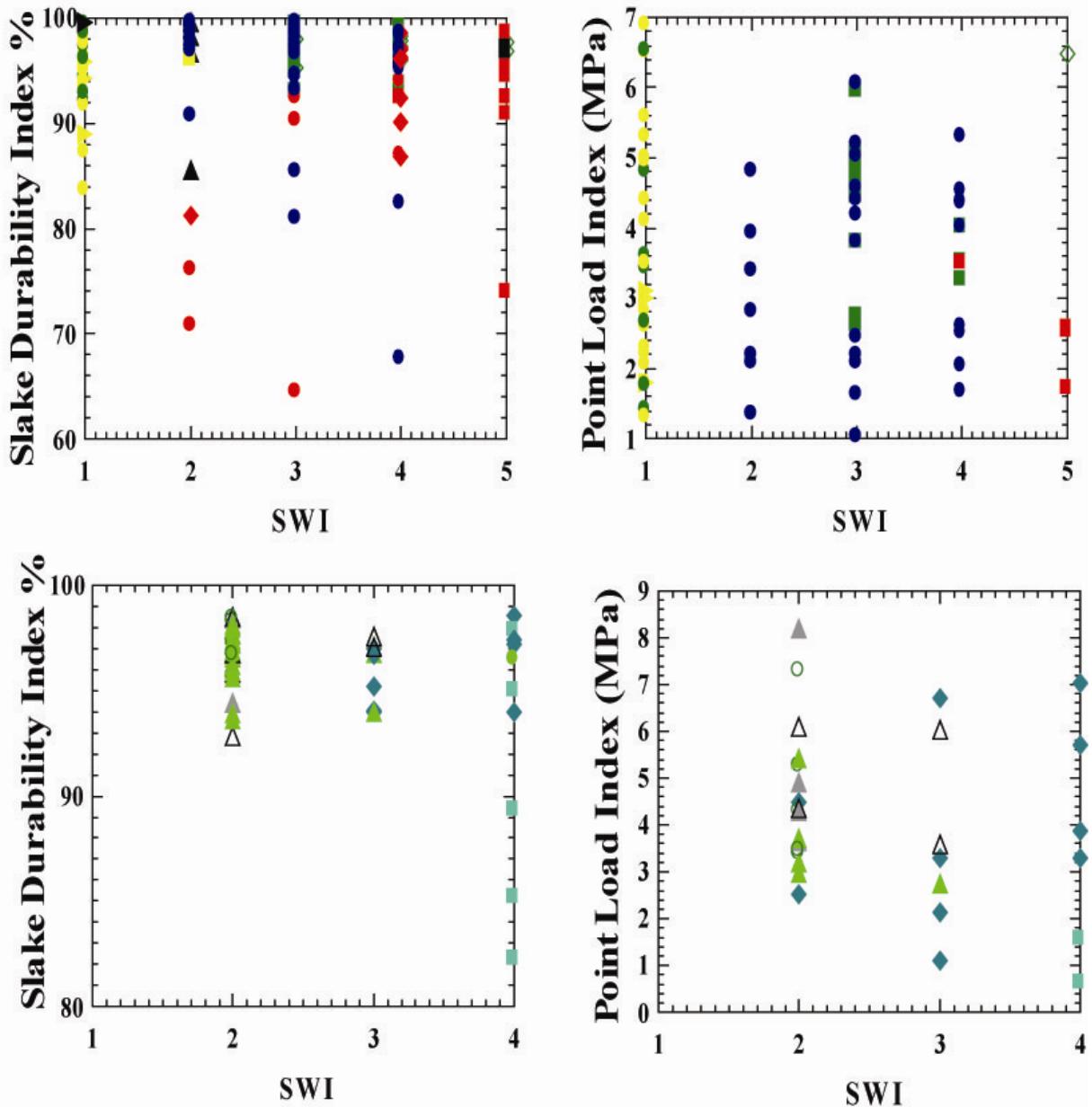


FIGURE 6. Variation in slake index, point load index and simple weathering indices (SWI) of the Questa rock materials. Some weathered samples, but not all, from the edge of GHN, other Questa rock piles, and analog materials show lower slake durability and point load indices. SWI index is explained in Appendix 2. The upper part of the figure is for the all the other rock pile location and the analogs except the GHN whereas the lower part is GHN.

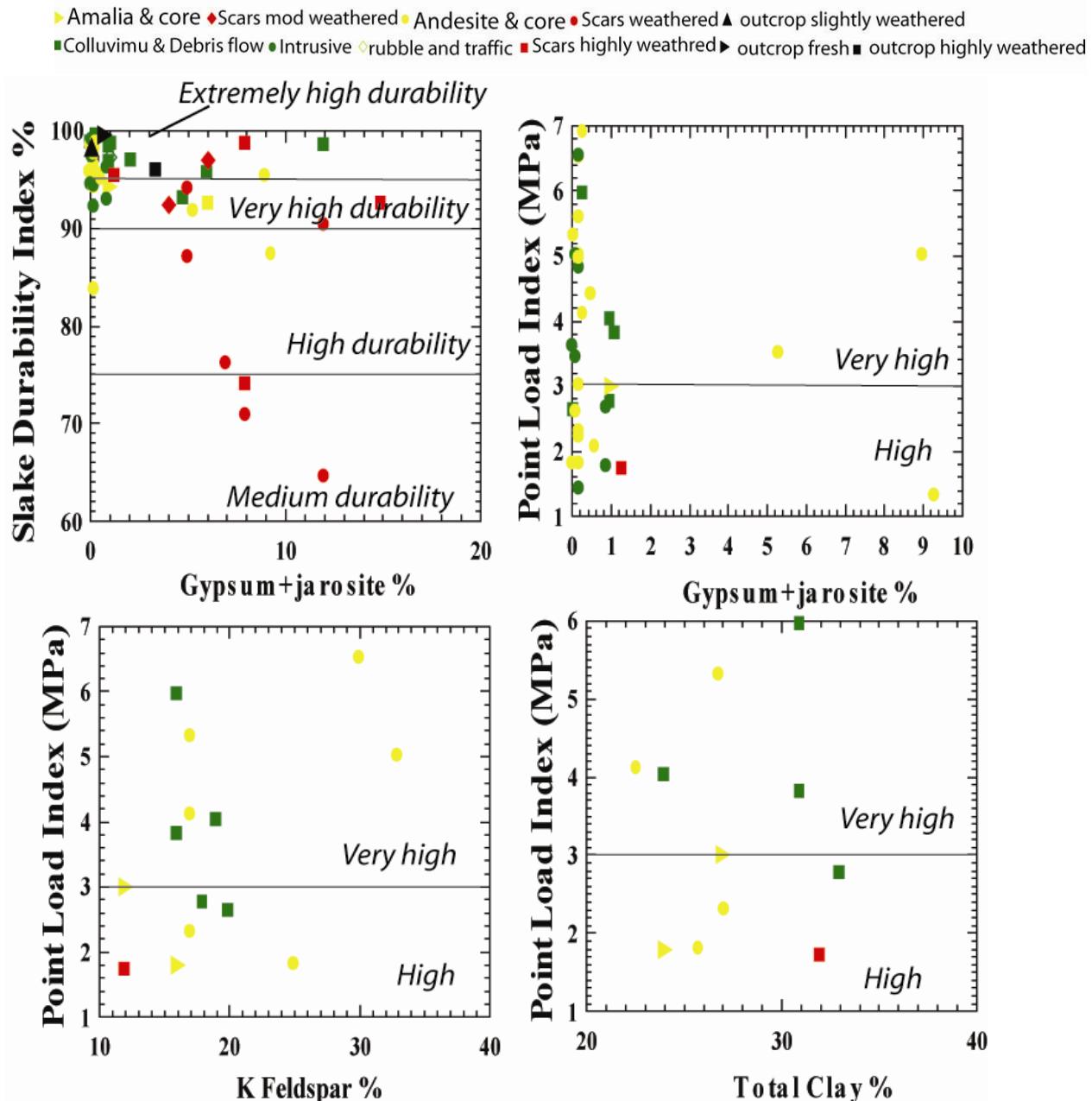


FIGURE 7. Variations between slake durability index, point load index, mineralogy, and chemistry. Gypsum + jarosite is an approximate measure of weathering of the Questa material; the higher the concentration, the more weathered the material is. These plots and other plots (G. Ayakwah et al., 2009) show that there are little if any correlations between slake durability and point load indices and mineralogy and chemistry of the tested materials.

■ C,I ▲ J,N ▲ M,O,Q ▲ K ○ R,S,P △ T,U,V,W ● Rock piles ■ Colluvium □ Core amalia ▨ Outcrop highly weathered
 ■ Scars highly weathered ● Scars weathered ◆ Scars mod. weathered ▲ Outcrop slightly weathered

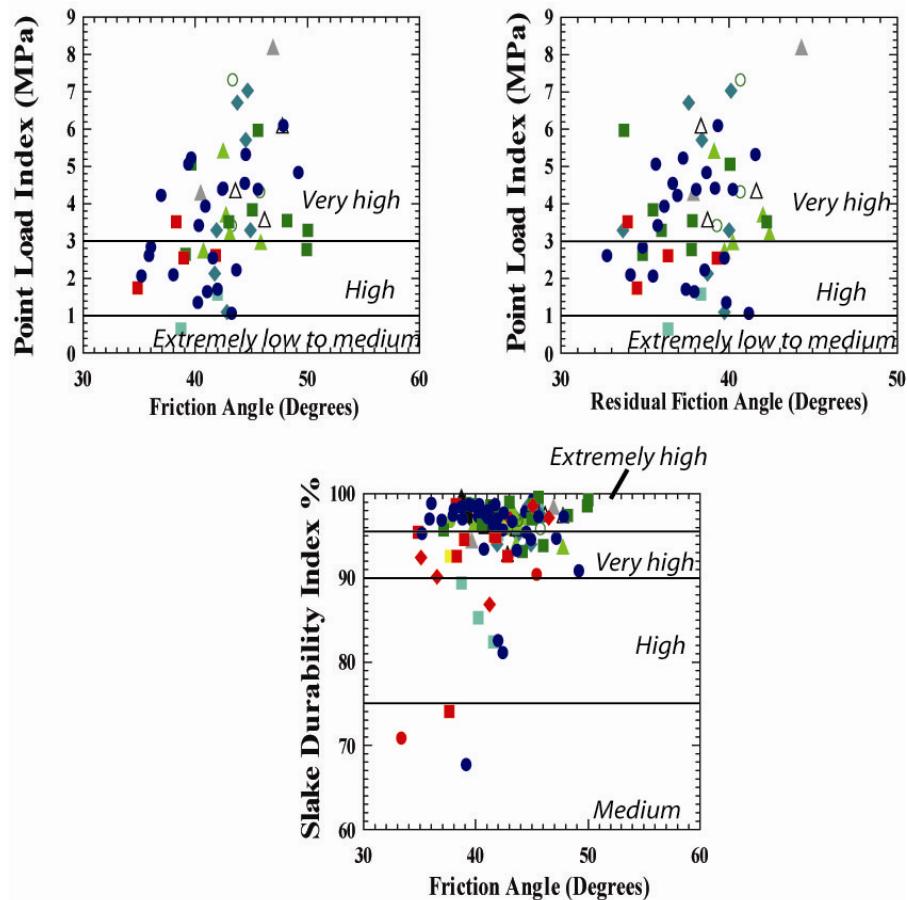


FIGURE 8. Variations between slake durability index, point load index, friction angle, and residual friction angle. The friction angle was determined on the fine-grained matrix, whereas the slake durability and point load indices were determined on larger rock fragments.

The samples tested include a wide range of hydrothermal alteration intensities that included clay minerals, locally as high as 30%. Most of the clay minerals are in the rock fragments as replacements of primary igneous minerals and the groundmass during hydrothermal alteration and would not be expected to affect shear strength, even though the clay mineral contents are so high (Fig. 9-11).

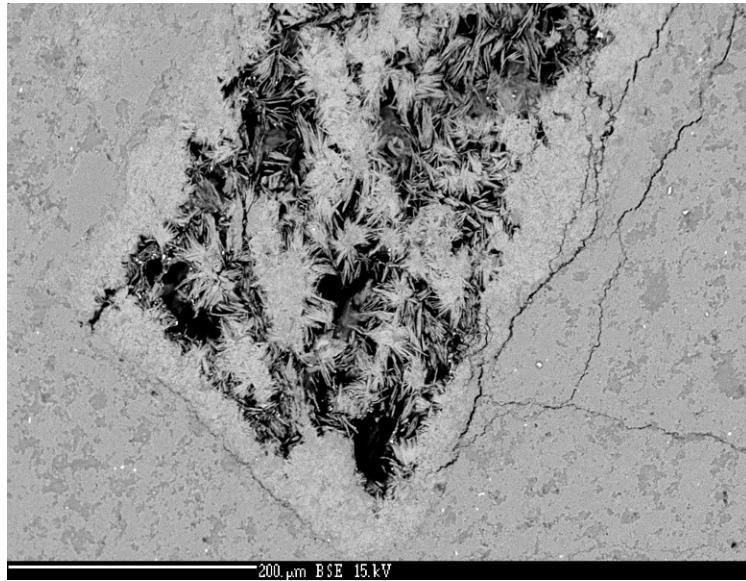


FIGURE 9. Clay minerals (mostly sericite) replacing feldspar phenocryst in QPS-altered rhyolite (Amalia Tuff; photo PIT-VCV-0004-30-01). This sample is an unweathered drill core sample of the ore body in situ before mining and has a slake durability index of 88.9%, point load index of 1.8 MPa, and total clay content of 24% (21% illite, 1% kaolinite, 1% chlorite, 1% smectite). SWI=1, QMWI=0

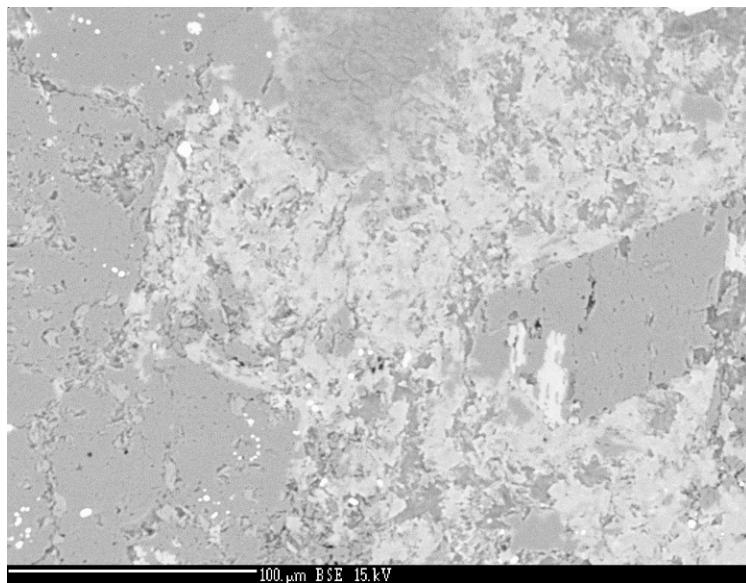


FIGURE 10. Clay minerals (mostly sericite and chlorite) replacing feldspar phenocryst in QSP-altered andesite (photo PIT-VCV-0001-30-02). This sample is an unweathered drill core sample of the ore body in situ before mining and has a slake durability index of 97.4%, point load index of 6.5 MPa, and total clay content of 20% (18% illite, 2% chlorite, no kaolinite or smectite). SWI=1, QMWI=6

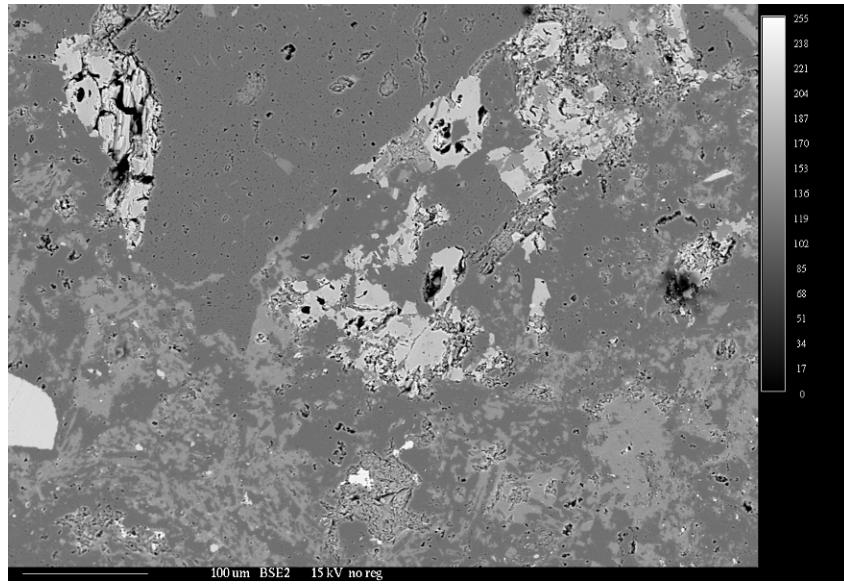


FIGURE 11. Clay minerals (mostly sericite and chlorite) replacing feldspar phenocryst in QSP- and prolytically-altered andesite from unit O of the GHN rock pile (photo GHN-KMD-0057-31-05). This sample has a slake durability index of 97.7%, point load index of 3.19 MPa, and total clay content of 21% (11% illite, 7% chlorite, 1% kaolinite, and 2% smectite). SWI=2. QMWI=1

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APPENDIX 1. METHODOLOGY IN CALCULATION OF POINT LOAD STRENGTH INDEX OF A SAMPLE

The plot of P versus D_e^2 of rock fragments of a sample generally results in a straight line but points around this line are usually scattered for weathered irregular rock fragments. Hence ISRM (1985) states that points that deviate from the straight line should be disregarded but should not be deleted. Figure 1-1 shows a plot of P versus D_e^2 with the entire data points and Figure 1-2 shows a plot with the removed deviated points. The average of I_{S50} values of these remaining points is the reported I_{S50} for each sample.

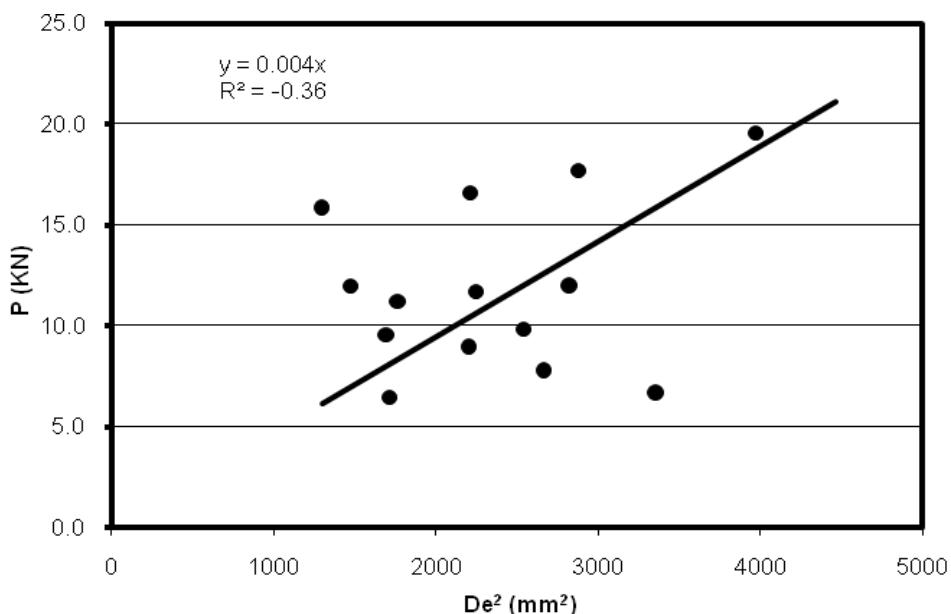


FIGURE 1-1. P (peak load) versus D_e^2 for sample MIN-SAN-0001 with 14 test points with graphical I_{S50} of 4.0 MPa and an average I_{S50} using the correction factor (equation 2) for the entire 14 tests of 4.82 MPa.

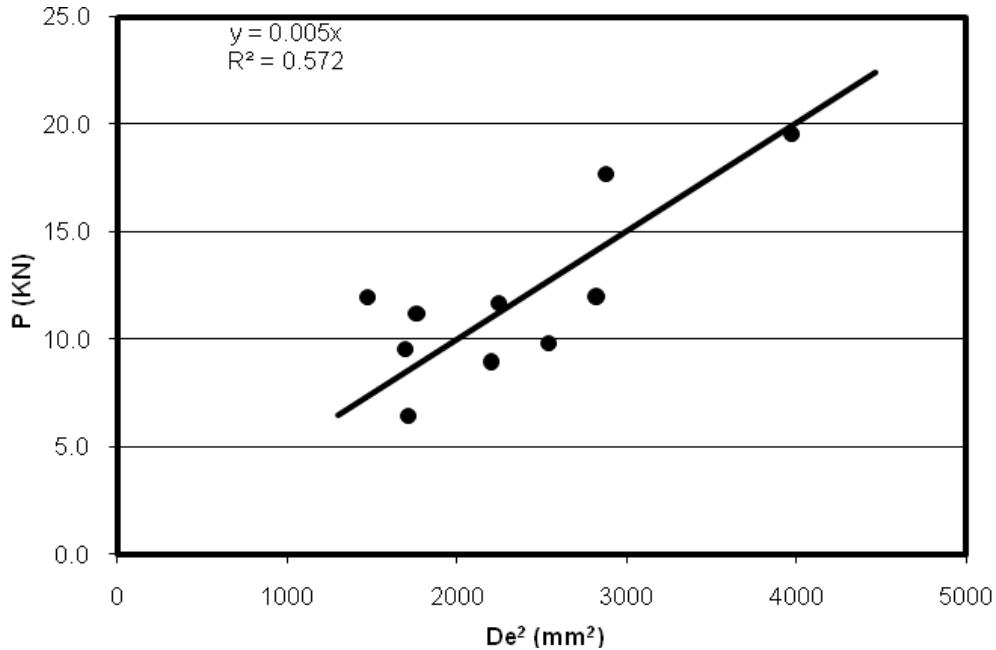


FIGURE 1-2. P (peak load) versus D_e^2 for sample MIN-SAN-0001 with 10 test points after eliminating the points deviating from the straight line with graphical I_{S50} of 4.0 MPa and an average I_{S50} using the correction factor (equation 2) for the 10 remaining points of 5.04 MPa. The reported I_{S50} for sample MIN-SAN-0001 is 5.04 MPa.

APPENDIX 2. ALTERATION AND WEATHERING OF THE QUESTA ROCK PILES

The Questa rock piles were formed by blasting of the overburden (material overlying the ore deposit), transported by truck, and dumped by end-haul methods over the edge of the slope into steep valleys near the Questa open pit (URS Corporation, 2003, appendix C). End-haul dumping results in a rock pile that consists of numerous layers that are matrix supported and finer in particle size at the top of the rock pile and increase in particle size and becomes more cobble supported at the base (McLemore et al., 2008a). The resulting layers locally are at, or near, the angle of repose and subparallel to the original slope angle. Detailed geologic mapping and sampling in the Goathill North (GHN) rock pile at Questa revealed that these layers could be defined as mappable geologic units in the rock pile (McLemore et al., 2008a). The overburden was fractured before blasting due to hydrothermal activity and intrusion of granitic porphyritic and aplitic rocks, resulting in angular rock fragments when blasted. The overburden was hydrothermally altered before mining (McLemore et al., 2008b). The mineralogical and chemical changes that occurred during hydrothermal alteration before mining are similar to the changes found during weathering of the rock-pile materials after mining.

Four different zones of weathering can be distinguished at GHN (Fig. 2-1):

- outer oxidized zone (includes the surface and geologic units C, I and J)
- intermediate zone (includes unit N)
- inner, less oxidized, weathered zone (includes units K-W)
- basal oxidized zone (includes geologic units R and rubble zone).

Weathering decreased from the outside to the inside of the stable portion of GHN and likely the other Questa rock piles. The base of GHN also is oxidized and weathered. Layers within the interior of the rock piles where air and water flowed also can be weathered.

Rock fragments in the GHN samples are comprised of two main lithologies, which are andesite and rhyolite (Amalia Tuff). Intrusive rocks, although present within colluvium/weathered bedrock, alteration scar, debris flows and other rock piles, are minor to absent within the GHN rock pile. All three rock types exhibit original igneous textures, although the andesite fragments have typically undergone significant hydrothermal alteration, whereas the rhyolite (Amalia Tuff) fragments are relatively pristine or consisted of QSP alteration. The rhyolite (Amalia Tuff) fragments consisted of large (~mm size) quartz and feldspar phenocrysts, surrounded by a devitrified glass matrix. Three types of alteration have been described at Questa, including propyllitic, quartz-sericite-pyrite (QSP), and argillic, although relict igneous textures are typically evident (McLemore et al., 2008b). Rough estimates of the intensity of these three alteration styles in the GHN rock pile were made petrographically. Although the ranges of intensity of alterations styles within a single rock pile unit are large, QSP alteration is the most prevalent style, and argillic is relatively minor. Propyllitic alteration is present throughout the pile, although, on average, at a lower intensity than QSP. There appears to be slightly more propyllitic alteration in the interior rock pile units (McLemore et al., 2008b).

It is difficult, but possible to distinguish between pre-mining hydrothermal alteration and post-mining weathering, by using detailed field observations and petrographic analysis that includes defining the paragenesis (sequence of events), especially using microprobe analyses (McLemore et al. 2008a, c). The evidence for weathering in the Questa rock piles includes (McLemore et al., 2008a, c):

- Change in color from darker brown and gray in less weathered samples (original color of igneous rocks) to yellow to white to light gray in the weathered samples
- Thin yellow to orange, “burnt” layers within the interior of GHN, where water and/or air flowed and oxidized the rock-pile material
- Paste pH, in general, is low in oxidized, weathered samples and paste pH is higher in less weathered samples
- Increase in abundance of jarosite, gypsum, Fe oxide minerals and soluble efflorescent salts (locally as cementing minerals), and low abundance to absence of calcite, pyrite, and epidote in weathered samples
- Tarnish or coatings of pyrite surfaces within weathered samples (Heizler et al., 2007)
- Dissolution textures of minerals (skeletal, boxwork, honeycomb, increase in pore spaces, fractures, change in mineral shape, accordion-like structures, loss of interlocking textures, pits, etching) within weathered samples (McLemore et al., 2008a)
- Change in bulk texture of the rock-pile material as compared to the original mined material, including increase in soil:rock ratio, piping or stoping within the rock pile, and decrease in grain size due to physical weathering
- Chemical classification as potential acid-forming materials using acid base accounting methods (Tachie-Menson, 2006)
- The chemical composition of waters from the Questa rock piles (i.e., seeps and runoff waters from the rock piles, chemistry of leachate waters obtained by laboratory leaching of rock pile samples) imply that silicate dissolution is occurring within the rock piles in a similar manner as that suggested by surface and ground water documented in the alteration scars by Nordstrom et al. (2005).

Not all weathered samples exhibit all of these features. It is common to have the fine-grained soil matrix be weathered, but the rock fragments within the rock-pile material exhibit little or no weathering.

In GHN, typically, paste pH increased with distance from the outer, oxidized units (west) towards the interior units (east) of the GHN rock pile. The outer units were oxidized (weathered) based upon the white and yellow coloration, low paste pH, presence of jarosite and authigenic gypsum, and absence of calcite. The base of the rock pile adjacent to the bedrock/colluvium surface represents the oldest part of the rock pile because it was laid down first. Portions of the base appeared to be nearly or as oxidized (weathered) as the outer, oxidized zone of the rock pile. This suggests that air and water flowed along the basal interface, implying that it must be an active weathering zone.

Numerous weathering indices were evaluated in the current research. A weathering index is a measure of how much a sample has weathered. Most of the weathering indices in the literature are based only on geochemical parameters, which restrict their application to the type of environment for which they were developed. A simple weathering index (SWI) was developed to differentiate the weathering intensity of Questa rock pile materials (SWI=1, fresh to SWI=5, most weathered; Table 2-1; Gutierrez et al, 2008). The 5 classes in Table 2-1 describes the SWI classification for the mine soils at the Questa mine based on relative intensity of both physical and chemical weathering (modified in part from Little, 1969; Gupta and Rao, 2001; Blowes and Jambor, 1990). These weathering indices actually measure both pre-mining hydrothermal alteration and post-mining weathering.

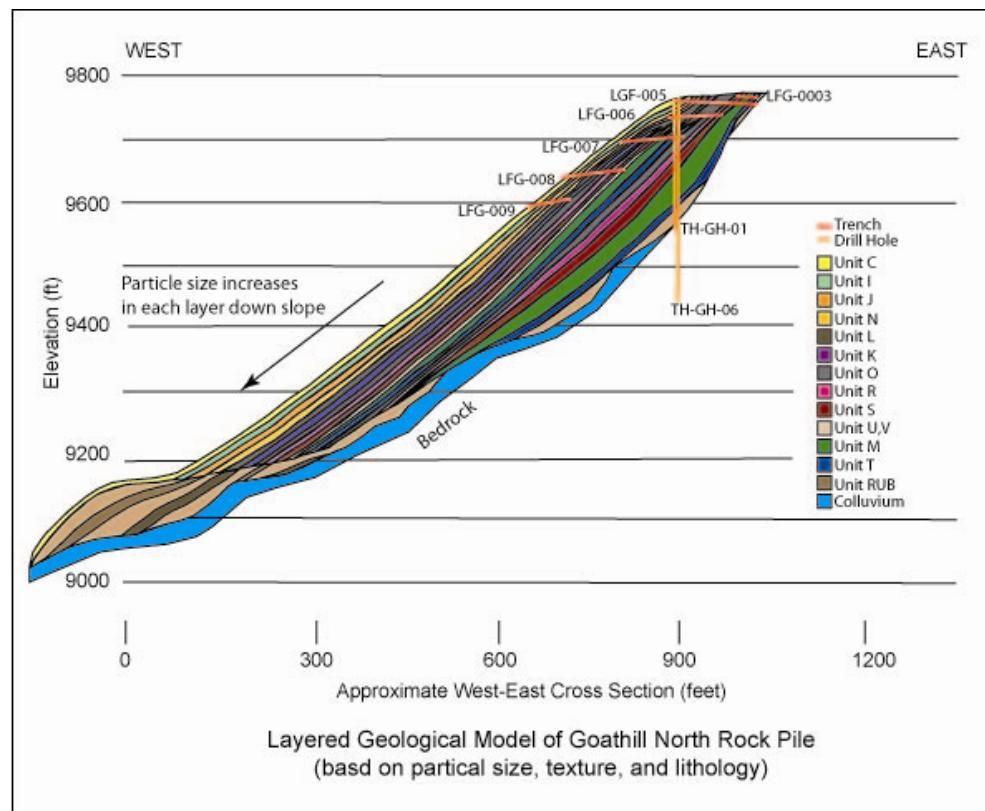


FIGURE 2-1. Conceptual geological model of GHN rock pile, as interpreted from surface mapping, detailed geologic cross section, trenches, drill holes, construction method and observations during reclamation of GHN.

TABLE 2-1. Simple weathering index for rock-pile material (including rock fragments and matrix) at the Questa mine.

SWI	Name	Description
1	Fresh	Original gray and dark brown to dark gray colors of igneous rocks; little to no unaltered pyrite (if present); calcite, chlorite, and epidote common in some hydrothermally altered samples. Primary igneous textures preserved.
2	Least weathered	Unaltered to slightly altered pyrite; gray and dark brown; angular to sub-angular rock fragments; presence of chlorite, epidote and calcite, although these minerals are not required. Primary igneous textures still partially preserved.
3	Moderately weathered	Pyrite altered (tarnished and oxidized), light brown to dark orange to gray; more clay- and silt-size material; presence of altered chlorite, epidote and calcite, but these minerals are not required. Primary igneous textures rarely preserved.
4	Weathered	Pyrite very altered (tarnished, oxidized, and pitted); Fe-hydroxides and oxides present; light brown to yellow to orange; no calcite, chlorite, or epidote except possibly within center of rock fragments (but the absence of these minerals does not indicate this index), more clay-size material. Primary igneous textures obscured.
5	Highly weathered	No pyrite remaining; Fe-hydroxides and oxides, shades of yellow and red typical; more clay minerals; no calcite, chlorite, or epidote (but the absence of these minerals does not indicate this index); angular to sub-rounded rock fragments

The SWI accounts for changes in color, texture, and mineralogy due to weathering, but it is based on field descriptions. Some problems with this weathering index are:

- It is subjective and based upon field observations.
- This index does not always enable distinction between pre-mining supergene hydrothermal alteration and post-mining weathering.
- The index is developed from natural residual soil weathering profiles, which typically weathered differently from the acidic conditions within the Questa rock piles and, therefore, this index may not adequately reflect the weathering conditions within the rock piles.
- This index refers mostly to the soil matrix; most rock fragments within the sample are not weathered except perhaps at the surface of the fragment and along cracks.
- The index is based primarily upon color and color could be indicative of other processes besides weathering intensity.
- This index was developed for the Questa rock piles and may not necessarily apply to other rock piles.
- Weathering in the Questa rock piles is an open not a closed system (i.e. water analysis indicates the loss of cations and anions due to oxidation).

Paste pH is another indication of weathering used in this project, but it has limitations as well. Paste pH is the pH measured from a paste or slurry that forms upon mixing soil material and deionized water. In an acidic material, paste pH is an approximate measurement of the acidity of a soil material that is produced by the oxidation of pyrite and other sulfides. A low paste pH (2-3) along with yellow to orange color and the presence of jarosite, gypsum, and low abundance to absence of calcite is consistent with oxidized conditions in the Questa rock piles

(McLemore et al., 2006a, b; Gutierrez et al., 2008). In general, paste pH increases from the outer, oxidized units of GHN to the inner, less oxidized units.

Changes of mineralogy and chemistry between the outer, oxidized zone and the interior, unoxidized zones of the rock piles are a result of differences due to pre-mining composition as well as chemical weathering. These differences can be difficult to distinguish, except by detailed field observations and petrographic analysis and the changes due to hydrothermal alteration are more pronounced than those due to weathering. Weathering processes, intensity, and rates will differ throughout the rock piles. Because weathering intensities and effects are so variable and dependent upon many factors, no single weathering index is valid over the entire spectrum of weathered states (Duzgoren-Aydin and Aydin, 2002). Therefore, several indices can be used to indicate some aspects of weathering in the Questa rock piles: SWI, paste pH, authigenic gypsum, sum of gypsum and jarosite, SO₄, and Net NP (neutralizing potential).

APPENDIX 3. SUMMARY STATISTICS OF THE STRENGTH AND SLAKE INDICES FOR QUESTA MATERIALS.

TABLE 3-1. Summary statistics of the strength classification for GHN rock pile samples. Geologic conceptual model is in Figure 2-1 (Appendix 2).

Location	Statistics	Point Load Strength Index
Unit I	No. of Samples	2
	Mean (MPa)	1.1
	Standard Deviation (MPa)	NA
	Minimum (MPa)	0.6
	Maximum (MPa)	1.6
	Coefficient of Variation (%)	NA
Unit J	No. of Samples	6
	Mean (MPa)	5.0
	Standard Deviation (MPa)	1.7
	Minimum (MPa)	3.3
	Maximum (MPa)	7.0
	Coefficient of Variation (%)	34.0
Unit N	No. of Samples	4
	Mean (MPa)	2.6
	Standard Deviation (MPa)	1.4
	Minimum (MPa)	1.1
	Maximum (MPa)	4.5
	Coefficient of Variation (%)	53.8
Unit K	No. of Samples	4
	Mean (MPa)	5.3
	Standard Deviation (MPa)	2.0
	Minimum (MPa)	3.7
	Maximum (MPa)	8.2
	Coefficient of Variation (%)	37.7
Unit O	No. of Samples	4
	Mean (MPa)	3.5
	Standard Deviation (MPa)	1.3

Location	Statistics	Point Load Strength Index
	Minimum (MPa)	2.4
	Maximum (MPa)	5.4
	Coefficient of Variation (%)	37.1
Unit R	No. of Samples	2
	Mean (MPa)	5.8
	Standard Deviation (MPa)	NA
	Minimum (MPa)	4.3
	Maximum (MPa)	7.3
	Coefficient of Variation (%)	NA
Unit S	No. of Samples	3
	Mean (MPa)	4.0
	Standard Deviation (MPa)	1.0
	Minimum (MPa)	3.4
	Maximum (MPa)	5.3
	Coefficient of Variation (%)	25.0
Unit U	No. of Samples	1
	Mean (MPa)	6.1
	Standard Deviation (MPa)	NA
	Minimum (MPa)	6.1
	Maximum (MPa)	6.1
	Coefficient of Variation (%)	NA
Unit UV	No. of Samples	2
	Mean (MPa)	5.3
	Standard Deviation (MPa)	NA
	Minimum (MPa)	4.5
	Maximum (MPa)	6.1
	Coefficient of Variation (%)	NA
Unit M	No. of Samples	1
	Mean (MPa)	3.7
	Standard Deviation (MPa)	NA
	Minimum (MPa)	3.7
	Maximum (MPa)	3.7
	Coefficient of Variation (%)	NA
Rubble	No. of Samples	1
	Mean (MPa)	6.5
	Standard Deviation (MPa)	NA
	Minimum (MPa)	6.5
	Maximum (MPa)	6.5
	Coefficient of Variation (%)	NA

TABLE 3-2. Summary statistics of the durability classification for GHN rock pile samples. Geologic conceptual model is in Figure 2-1 (Appendix 2).

Units	Statistics	Slake Durability Index
Traffic	No. of Samples	2
	Mean (%)	97.0

	Standard Deviation (%)	NA
	Minimum (%)	96.0
	Maximum (%)	98.0
	Coefficient of Variation (%)	NA
Unit C	No. of Samples	1
	Mean (%)	97.9
	Standard Deviation (%)	NA
	Minimum (%)	97.9
	Maximum (%)	97.9
	Coefficient of Variation (%)	NA
Unit I	No. of Samples	4
	Mean (%)	87.9
	Standard Deviation (%)	5.5
	Minimum (%)	82.2
	Maximum (%)	95.0
	Coefficient of Variation (%)	6.3
Unit J	No. of Samples	7
	Mean (%)	95.8
	Standard Deviation (%)	1.9
	Minimum (%)	94.0
	Maximum (%)	98.5
	Coefficient of Variation (%)	2.0
Unit N	No. of Samples	5
	Mean (%)	96.3
	Standard Deviation (%)	1.4
	Minimum (%)	94.0
	Maximum (%)	98.5
	Coefficient of Variation (%)	1.5
Unit K	No. of Samples	5
	Mean (%)	96.2
	Standard Deviation (%)	2.2
	Minimum (%)	93.6
	Maximum (%)	98.4
	Coefficient of Variation (%)	2.3
Unit O	No. of Samples	18
	Mean (%)	96.5
	Standard Deviation (%)	1.4
	Minimum (%)	93.6
	Maximum (%)	98.1
	Coefficient of Variation (%)	1.5
Unit R	No. of Samples	2
	Mean (%)	96.4
	Standard Deviation (%)	NA
	Minimum (%)	95.5
	Maximum (%)	97.3
	Coefficient of Variation (%)	NA
unit S	No. of Samples	3
	Mean (%)	97.4

	Standard Deviation (%)	1.6
	Minimum (%)	95.6
	Maximum (%)	98.4
	Coefficient of Variation (%)	1.6
Unit U	No. of Samples	5
	Mean (%)	97.7
	Standard Deviation (%)	0.6
	Minimum (%)	97.1
	Maximum (%)	98.5
	Coefficient of Variation (%)	0.6
Unit UV	No. of Samples	3
	Mean (%)	96.7
	Standard Deviation (%)	0.8
	Minimum (%)	95.9
	Maximum (%)	97.4
	Coefficient of Variation (%)	0.8
Unit M	No. of Samples	1
	Mean (%)	96.6
	Standard Deviation (%)	NA
	Minimum (%)	96.6
	Maximum (%)	96.6
	Coefficient of Variation (%)	NA
Rubble	No. of Samples	7
	Mean (%)	97.4
	Standard Deviation (%)	1.1
	Minimum (%)	95.2
	Maximum (%)	98.5
	Coefficient of Variation (%)	1.1
Colluvium	No. of Samples	9.0
	Mean (%)	95.7
	Standard Deviation (%)	1.7
	Minimum (%)	93.0
	Maximum (%)	98.5
	Coefficient of Variation (%)	1.8
Unstable GHN	No. of Samples	11
	Mean (%)	95.7
	Standard Deviation (%)	5.1
	Minimum (%)	80.9
	Maximum (%)	99.2
	Coefficient of Variation (%)	5.3
Unit P	No. of Samples	1
	Mean (%)	96.7
	Standard Deviation (%)	NA
	Minimum (%)	96.7
	Maximum (%)	96.7
Unit H	No. of Samples	1
	Mean (%)	96.5

	Standard Deviation (%)	NA
	Minimum (%)	96.5
	Maximum (%)	96.5
	Coefficient of Variation (%)	NA

TABLE 3-3. Summary statistics of the strength classification for all rock pile samples. Location of Questa rock piles are shown in Figure 1.

Rock Pile Location	Statistics	Point Load Strength Index
Goat Hill North (GHN)	No. of Samples	31
	Mean(MPa)	4.3
	Standard Deviation (MPa)	1.9
	Minimum (MPa)	0.6
	Maximum (MPa)	8.2
	Coefficient of Variation (%)	43.4
Spring Gulch (SPR)	No. of Samples	7
	Mean(MPa)	3.0
	Standard deviation (MPa)	1.2
	Minimum (MPa)	1.3
	Maximum (MPa)	4.8
	Coefficient of Variation (%)	38.8
Sugar Shack South	No. of Samples	8

(SSS)	Mean(MPa)	2.2
	Standard Deviation (MPa)	0.8
	Minimum (MPa)	1.0
	Maximum (MPa)	3.8
	Coefficient of Variation (%)	35.9
Sugar Shack West (SSW)	No. of Samples	11
	Mean(MPa)	4.2
	Standard Deviation (MPa)	1.3
	Minimum (MPa)	2.0
	Maximum (MPa)	6.1
	Coefficient of Variation (%)	31.0
Middle (MID)	No. of Samples	2
	Mean(MPa)	4.5
	Standard Deviation (MPa)	NA
	Minimum (MPa)	4.4
	Maximum (MPa)	4.5
	Coefficient of Variation (%)	NA

TABLE 3-4. Summary statistics of the durability classification for all rock pile samples. Location of Questa rock piles are shown in Figure 1.

Location	Statistics	Slake Durability Index
GHN	Number of Samples	76
	Mean (%)	96.1
	Standard Deviation (%)	3.2
	Minimum (%)	80.9
	Maximum (%)	99.2
	Coefficient of Variation (%)	3.4
SPR	Number of Samples	8
	Mean (%)	96.1
	Standard Deviation (%)	5.2
	Minimum (%)	83.5
	Maximum (%)	99.2
	Coefficient of Variation (%)	5.4
SSS	Number of Samples	30
	Mean (%)	97.7
	Standard Deviation (%)	2.7
	Minimum (%)	85.3
	Maximum (%)	99.5
	Coefficient of Variation (%)	2.7
SSW	Number of Samples	18
	Mean (%)	96.4
	Standard Deviation (%)	3.8
	Minimum (%)	82.3
	Maximum (%)	98.7
	Coefficient of Variation (%)	4.0
MID	Number of Samples	3

Location	Statistics	Slake Durability Index
	Mean (%)	96.9
	Standard Deviation (%)	1.1
	Minimum (%)	95.6
	Maximum (%)	97.6
	Coefficient of Variation (%)	1.1