Executive Summary

Table ES.1. Review of Pebble Limited Partnership's Environmental Baseline Document (EBD): Geochemical characterization

Basic issue	What are the geochemical characteristics of the Pebble deposit and surrounding rocks, and how do those characteristics influence their potential environmental behavior under mining conditions?
Approach, data quality, and intended uses	Acid-base accounting and short-term leach tests followed accepted approaches, and the results are of high quality. The longer-term leach tests used non-standard methods or modifications, and more explanation of the methods is needed. Samples selected for long-term leach testing were not representative of the full variability of acid-generation potential or metal content of the deposit as a whole. Intended uses, especially predicting representative mine water quality and the potential for long-term contaminant leaching, are hampered by the size of the mined resource examined (only one-half the full resource size), sample representation, and the way in which geochemical test units were defined.
Primary data gaps	No results are presented for Pebble ore, and no short- or long-term leach test results are presented for pyritic tailings. Bioassay results for tailings supernatant were not included in the EBD. More mineralogic information and expanded long-term leach testing are needed.
Principal findings and recommendations	All ore host rocks and some surrounding rocks and tailings are potentially acid generating. Acidic conditions developed rapidly for an important subset of the samples. Host rocks leached high metal concentrations (> 100 times water quality criteria for copper) under acidic conditions and even under subaqueous conditions if acidic conditions develop before submergence. Selenium leachate concentrations were highest in surrounding rocks under neutral pH conditions. The high acid generation and contaminant leaching potential poses a substantial threat to aquatic life. No commonly used and easily measured parameters have strong relationships with long-term leachate concentrations. Reconfigured testing units should be defined, based on expanded mineralogic, hydrothermal alteration, and whole rock chemistry information, and additional long-term leach testing should be conducted. Samples should include ore and tailings (both bulk and pyritic) and be representative of the full range of acid generation and contaminant leaching potential so the long-term environmental behavior all types of mined material is known. The resulting data should be reviewed to determine if an easily measured parameter that correlates well with acid generation and metal leaching potential can be used to guide field management of mined materials.

Introduction

This review summarizes and evaluates the geochemical characterization information in the Pebble Project Environmental Baseline Document (EBD), including information in Chapter 11 (Geochemical Characterization, Bristol Bay Drainages; PLP, 2011a) and Chapter 8 of Appendix E [Consolidated Study Program (CSP), Geochemical Characterization and Metal Leaching/Acid Rock Drainage; PLP, 2011b). Together these documents comprise over 2,000 pages of information related to the potential of the Pebble deposit to generate acid and leach metals and other constituents. Unlike other sections of the EBD that present information on existing pre-mining conditions, the geochemical characterization program relies on a mine plan and provides information on the predicted environmental behavior of the mined material during operation, closure, and post-closure.

According to the EBD, the intended uses of the geochemical characterization data include evaluating the potential for metal leaching and acid drainage and the potential for adverse environmental effects from mine management facilities; predicting representative water quality from mined materials; and assessing alternative management plans and developing engineering and mitigation measures that could minimize potential effects from mine operations and closure (PLP, 2011b). Additional objectives and intended uses include informing the engineering design of water management, linking laboratory test data to field conditions (Day and Linklater, 2012), and evaluating the behavior of pit walls under submerged conditions (PLP, 2011a). Although not mentioned explicitly in the EBD, results from geochemical characterization programs are also used to inform the type and extent of water treatment that could be necessary during and after operations (U.S. EPA, 2003, Appendix D).

The purpose of this review is to evaluate the overall approach and implementation of the geochemical characterization program, evaluate the quality of the data generated by the program and the intended uses, and identify major findings and data gaps.

The length of the sections on geochemical characterization and the length of this review necessitate that not all aspects of the EBD geochemistry program are evaluated at the same level of detail. The review focuses on points that are most important for estimating the potential effects of mine development on water quality and fish populations.

Criteria for Evaluation of the Pebble EBD Geochemical Characterization Program

There are no mandatory requirements for the design or implementation of a geochemical characterization program, and there are no prescribed testing or analytical methods that must be used as part of the program. However, regulators and the mining industry do rely on a limited set of guidance and references as accepted and standard practice. Some of most commonly used references for the overall design of geochemical testing programs include the U.S. Environmental Protection Agency's (EPA's) Source Book for Industry in the Northwest and

Alaska and associated appendices (U.S. EPA, 2003); Natural Resource Canada's Mine Environment Neutral Drainage (MEND) program (e.g., MEND, 2009); and the International Network for Acid Prevention's (INAP's) Global Acid Rock Drainage (GARD) Guide (INAP, 2012). The Acid Drainage Technology Initiative (ADTI) is developing a guide on techniques for predicting metal mining influenced water, but the draft is not yet available (ADTI, 2012).

The EBD geochemical characterization program relied on U.S. EPA (2003) as the basis for the testing program (PLP, 2011b). According to the EBD, the geochemical testing methods followed those documented by "the American Society for Testing and Materials (ASTM), Environmental Protection Agency, or the Mine Environment Neutral Drainage (MEND) program" (PLP, 2011b). SRK Consulting of Vancouver, Canada, designed and managed the testing program.

Brief Summary of the Pebble Project Geochemical Characterization Program

The following types of geochemical characterization tests were conducted as part of the program.[1] The numbers in parentheses after each test indicate the total number of samples.

- **Static testing**: Static tests characterize the total amounts of constituents and amounts of acid or neutralizing potential in the rocks but do not address how those components will be released from the rocks over the long-term. Static testing included whole rock chemical analysis (total concentrations of constituents in the samples; sample numbers not listed in the EBD); mineralogic analysis (77); acid-base accounting tests (1,104), including Sobek and modified Sobek methods; and short-term leach tests (120), including shake-flask extractions, sequential net acid generation (NAG), and meteoric water mobility procedure (MWMP) tests. Shake-flask extractions were only conducted on older weathered waste rock; the sequential NAG tests were conducted on the same materials as the shake-flask extractions.

- **Kinetic testing**: Kinetic tests characterize the longer-term leaching ability and rates of release of constituents in samples under different geochemical conditions. Kinetic testing included humidity cell tests (HCTs; 84), stored bag weathering tests (20), subaqueous column tests (8), aerated column tests (2), and field (barrel) tests (10). Stored bag tests were performed only on Pebble East waste rock. Aerated column tests were only conducted on Pebble West tailings. Field barrel tests were conducted on Pebble West waste rock (Pre-Tertiary[2] and Tertiary) and Pebble East Tertiary waste rock.

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1. See Table 11-16 in the EBD for numbers in each category; also see Chapter 11 for descriptions of the tests. However, the design of the testing program is not spelled out clearly in Chapter 11 or Appendix E, Chapter 8 of the EBD.

2. The ore host rocks are Pre-Tertiary volcanic-sedimentary and volcanic rocks. The younger Tertiary rocks overlie the Pre-Tertiary rocks and ore and are volcano-sedimentary, sedimentary, and volcanic flow rocks (PLP, 2011a).

Evaluation and Implications

This review evaluates four major geochemical characterization issues and their environmental implications: (1) testing methods used, (2) sample representativeness, (3) contaminant leaching potential, and (4) time to onset of acid drainage.

1. Testing methods

In general, the *static* geochemical testing (acid-base accounting, mineralogic analysis, whole rock chemistry, short-term leach tests) conducted for the EBD used standard accepted methods for prospective and existing mine sites, and the data are of high quality. However, all methods used for *kinetic* testing (HCTs, stored bag tests, column tests, field barrel tests) were non-standard or had non-standard modifications. For all HCTs except those on the subsamples from the field barrel tests, a modification of the ASTM D5744-96 humidity cell procedure was used that tested more material (5 kg rather than 1 kg;) and larger particle sizes (-3/8 rather than -1/4 inch; PLP, 2011a, Section 11.6.4.6) than called for in the ASTM standard method. The larger mass of material should not make a difference because the water:solid ratios were the same, although the larger column sizes will change the amount of rock that the leachate contacts in the column (Maest et al., 2005). The explanation given for the modification was that "there was a concern that a disproportionate amount of internal grain matrix would be exposed, which would be less representative of mined materials" (PLP, 2011a, Section 11.6.4.6). Such a situation could be true if metal sulfides coated fractures and the majority of the neutralizing material was in the rock matrix. However, the Pebble ore that has been characterized is largely a disseminated ore body (Wardrop, 2011), where both acid-producing and acid-neutralizing minerals are in the rock matrix. A larger particle size could result in the HCTs giving lower weathering/contaminant release rates due to the lower surface area per unit volume. The contaminant release rates measured in the HCTs are important because they were used to estimate the time to onset of acid drainage. The lower the release rate, the longer the predicted time to onset of acid drainage (PLP, 2011a). Therefore, the use of larger particles in the HCTs could suggest that management methods to control acid drainage were not necessary for a number of years, when they could be required sooner.

No method references were provided for the remainder of the kinetic testing, including the stored bag weathering tests, the subaqueous column tests, the aerated column tests, and the field barrel tests. These are non-standard tests with no commonly accepted methodology; therefore, more detailed method descriptions should have been provided in the CSP (Appendix E) or the EBD (Chapter 11 or Appendix G). Without test method details, the appropriateness of the methods used for these kinetic tests cannot be evaluated.

2. Sample representativeness

This section describes four reasons why the geochemical samples may not be representative of material and conditions encountered during possible mining of the Pebble deposit. According to U.S. EPA (2003), "applicants should demonstrate that the samples characterized are representative of materials that will be produced during operations…[and] are expected to describe the variability…that may have been imparted to a lithological unit through weathering, hydrothermal alteration, and mineralization." The selection of appropriate geochemical testing units is the first, and arguably the most important, step in a characterization program (Maest et al., 2005; INAP, 2012). If the geochemical testing program samples are not representative of the physical extent of the operation, the mineralization and alteration of the deposit area, the volume of rock units, the potential to leach contaminants, and the types of proposed mined materials, the predictive power of the results can be severely limited.

Representativeness of operation size and location. The geochemical testing program is based on the 4.48 billion ton reserve (PLP, 2011b), which is only approximately half that of the total resource (Wardrop, 2011). One of the stated objectives of the geochemical testing program is to "determine the amount and types of representative mine rock and ore that may be anticipated over a mine life based on the ultimate resource (including the potential limits of an open pit and underground workings)" (PLP, 2011b, Section 8.2). Applying the results from the geochemical testing program to the total resource will cause errors in the estimated percentages of rock and alteration types on the ultimate pit surface and the walls of the underground workings, and will result in errors in the prediction of mine water quality, which could affect water treatment and waste management plans.

Selection of geochemical test units. The geochemical testing program is not representative of the variability in geochemical characteristics and environmental behavior of the mined materials. The EBD's geochemical testing program is based only on rock type and sulfur content and does not take hydrothermal alteration into account. Hydrothermal alteration can control mineralogy and rock texture and therefore weathering rates, contaminant leaching, and net acid-generation potential. Hydrothermal alteration is often associated with ore formation, and results from circulating hot fluids that dissolve the original minerals and form new ones that are more stable under the new conditions (Barnes, 1979). Portions of the same rock unit (e.g., granodiorite) can be affected and unaffected by hydrothermal alteration and produce areas, for example, with higher and lower sulfide and carbonate mineral contents. The EBD program makes some attempt to capture the variability in sulfur content but does not consider other effects of hydrothermal alteration, such as shifts in the amounts of neutralizing minerals. The Wardrop report devotes a chapter (Chapter 9) and six figures to the effects of hydrothermal alteration on the geochemistry of the Pebble deposit and surrounding rocks. The EBD, on the other hand, simply lists the eight major alteration types with no further discussion (PLP, 2011c, Section 3.7.5). In the Pebble deposit, for example, hydrothermal alteration has increased the amount of pyrite (the primary mineral that forms acid drainage) on the edge of the deposit, and post-hydrothermal weathering

has formed an oxidized cap (PLP, 2011a). Hydrothermal alternation is likely a more important control on the geochemical behavior of mined materials at Pebble than is lithology.

The EBD testing program does not follow EPA guidance on capturing the chemical variability of each geologic/lithologic unit that will be encountered. According to U.S. EPA (2003), "applicants will need to consider how vertical and lateral changes in the intensity and style of mineralization and host rock alteration affect the acid generating characteristics and metals leachability of each geologic unit at the proposed mine site." They propose that the best way to accomplish this is mineralogic analysis, which can be used to "quantify the range and median proportions of acid-forming, acid neutralizing, and metal-bearing constituents in the various lithological units that will be encountered." The testing program in the EBD analyzed only 77 samples for mineralogic analysis (see Table 11-16, PLP, 2011a) in a total of 27 identified rock types (see Table 11-1, PLP, 2011a). Seventy seven mineralogic samples is a relatively small number for characterization, particularly for a proposed mine as large as this one. By comparison, at a much smaller copper-gold prospect in British Columbia (Prosperity Project, Taseko Minerals), Canada, SRK Consulting did mineralogy on a total of 417 samples (Taseko Mines, 2009). The majority of the effort at the Prosperity Project focused on identifying carbonate minerals to determine the true extent of their neutralization potential.

Further, graphs in Appendix 11K (PLP, 2011a) show that there is substantial chemical variability in the PLP-selected Pre-Tertiary test units in terms of mean sulfide, copper, molybdenum, and arsenic content. The tri-modal sulfur distribution in Pebble East granodiorite suggests that there are subunits within the lithology that should constitute separate geochemical test units. Such variability suggests that the *Pre-Tertiary* rocks need to be split into different and likely additional testing units. The results for the *Tertiary* rocks shown in Appendix 11K suggest the opposite in many cases – that fewer geochemical test units could have been used because there is lower variability in total sulfur, copper, molybdenum, and arsenic contents. Alteration type was noted in the drill core logs and entered into the Northern Dynasty Mines Pebble Project Drill-Core Database (PLP, 2011a); this information should have been used to define geochemical test units and select samples for static and kinetic testing. More mineralogic analysis is needed, and those results, combined with drill core information, should be used to reconfigure the geochemical test units. Testing should then begin based on the new test units, which could span more than one lithology.

Representativeness of acid drainage and contaminant leaching potential. Samples in the testing program should be representative of the full variability in geochemical characteristics (U.S. EPA, 2003), and the EBD HCT selection is not representative of higher acid generation and copper leaching potentials in the deposit. Materials with higher acid generation and metal leaching potential will generate lower pH values and higher metal concentrations, and if they are not represented in the testing program, mine water quality will be predicted to be better than it will be under mining conditions. As shown in Figure 1, HCT samples are not representative of the higher %S or total Cu values.

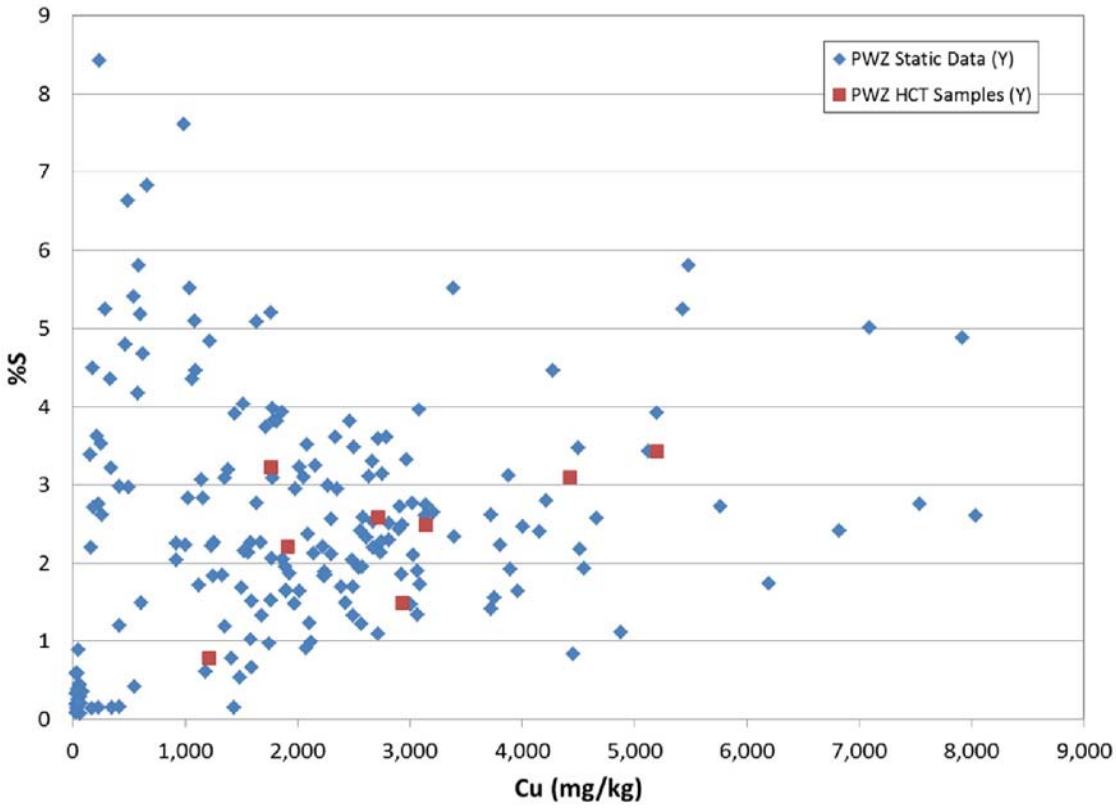

Figure 1. Pebble West Zone (PWZ) static and HCT comparison for samples from units containing Pre-Tertiary mudstone (Y): % sulfur and copper. This figure shows that PWZ HCT samples are not representative of higher %S and copper concentrations, and results could therefore underestimate releases of acidity and copper concentrations in mine water.

Source: PLP, 2011a, Chapter 11.

The EBD states that, for the Pre-Tertiary rocks, granodiorite and mudstone were the most volumetrically important units (PLP, 2011a), but no quantitative information is provided in the EBD on amounts of each rock type, which can be used to set sample numbers for testing (U.S. EPA, 2003). Limited information is provided on the number of core intervals for each testing unit for the Pebble East Zone (PEZ). As shown at the bottom of Table 1, HCTs were conducted on only a single higher copper sample (out of 13), whereas the drill core data show that 69% of the drill core intervals had higher copper concentrations. Therefore, Pre-Tertiary samples with higher copper concentrations were dramatically under-represented in the HCT samples.

Table 1. Comparison of number of drill core intervals in lower (CuEQ < 0.6%) and higher (CuEQ > 0.6%) copper PEZ samples with selected PEZ HCT samples

Pre-Tertiary rock type	Symbol	CuEQ < 0.6% # intervals drill core	CuEQ > 0.6% # intervals drill core
Granodiorite	G	1,775	3,978
Mudstone	Y	723	1589
Diorite	D	11	67
Porphyritic monzodiorite	P	62	0
Wacke	W	74	138
Fault zone	Z	37	62
Total		2,682	5,834
% of each CuEQ		31%	69%
# HCTs in each CuEQ[a]		12	1
% of HCT samples in each CuEQ		92%	8%

a. According to Wardrop (2011, Table 1.6.1), a cut-off CuEQ of 0.60% for measured and indicated resources would have a Cu content of 0.55%, which is equivalent to 5,500 mg/kg Cu. Only 1 of 13 PEZ Pre-Tertiary HCT samples, 220841 (mudstone), had a copper concentration above this cutoff.

Sources: PLP, 2011a, Tables 11-3, 11-4, 11-12; Wardrop, 2011.

As shown in Figure 2, the samples selected for HCTs also do not capture the full variability of the NP or AP of the deposit as a whole. No samples were selected in the "uncertain" range (between NP:AP ratio of 1 to 3) or the higher NP:AP ratio range, and importantly, there are no samples in the lowest NP:AP range, which is more likely to generate lower pH values and leach higher metal concentrations.[3] This lack of variability may partially explain why no commonly used and easily measured parameters (such as %S) have strong relationships with HCT leachate concentrations. Samples that are representative of the full range of acid generation and contaminant leaching potential should be subjected to HCTs and other types of long-term leach tests so the long-term environmental behavior all types of mined material is known. The data should then be reviewed to determine if an easily measured parameter that correlates well with acid generation and metal leaching potential can be used to guide field management of mined materials.

3. Kinetic testing often focuses on static samples in the uncertain range where NP and AP are similar, and only kinetic testing will determine whether the materials will form acid over the long term; there are no HCT samples in the uncertain range. Humidity cell leachate concentrations are also used to estimate water quality in the pit, underground workings, etc., so it is important to test the full range of NP:AP ratios.

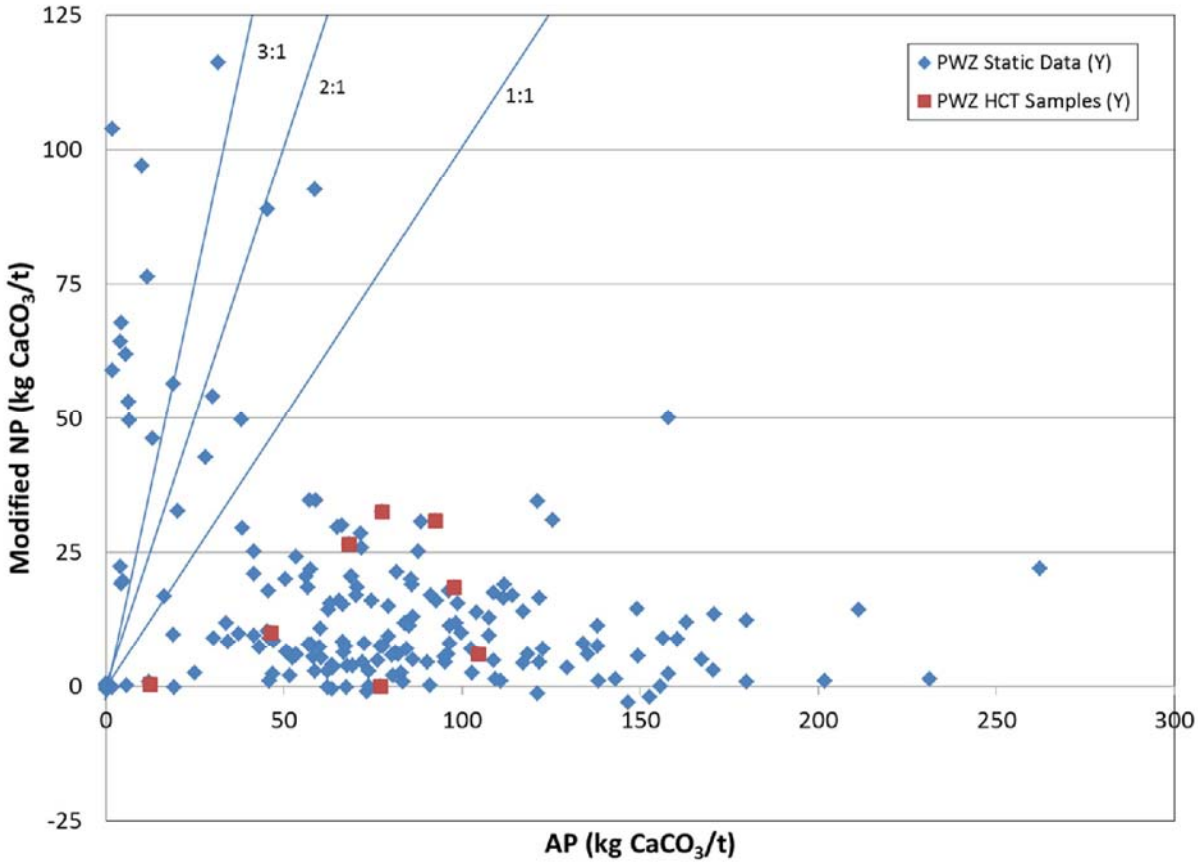

Figure 2. PWZ static and HCT comparison for samples from units containing Pre-Tertiary mudstone (Y): modified NP and AP. Lines represent 1:1, 2:1, and 3:1 NP:AP ratios. This figure shows that PWZ HCT samples, which are used to estimate longer term environmental behavior, are not representative of mined materials with uncertain, higher NP:AP, or lower NP:AP ratios.

Source: PLP, 2011a, Chapter 11.

Representativeness of proposed mine wastes and mined materials. Although the CSP (PLP, 2011b, Section 8.2.1) states that materials representative of ore stockpiles, process tailings, walls and floors of the underground workings, and broken rock produced by block-caving were evaluated as part of the testing program, no information on ore or on the leaching characteristics of pyritic tailings was actually included in the EBD.

No samples of pyritic tailings or of the ore were tested for leachate potential. Gold is associated with pyrite (Wardrop, 2011), and pyritic tailings could be an important waste type for the operation. The omission of ore leachate testing contradicts U.S. EPA (2003) guidance, which

states that "applicants should test ore samples that capture the range of ore grades that will be processed during the life of the mine." Ore should be subjected to the same types of geochemical tests as other materials, especially in the PEZ, because, as noted in Chapter 8 of Appendix E (PLP, 2011b), "possible underground mining methods such as block caving presumably will result in broken, ore-grade rock remaining in the mine."

In summary, the geochemical testing program for the Pebble deposit area is far from representative of the full range of potentially mined material types or their geochemical characteristics. Because the testing program is based on only one-half of the total resource, any geochemical differences between the assumed pit surface and the ultimate pit surface should be clearly described. There is a fundamental flaw in the design of the testing program that severely limits the predictive power of the results: the geochemical test unit selection relied solely on lithology and sulfur content and did not include information on hydrothermal alteration. Substantially more mineralogic and drill core log (alteration) information should be used to assign new Pre-Tertiary geochemical test units based on hydrothermal alteration, mineralization, lithology, and the full resource size. Samples from these units should be subjected to the same array of static and kinetic testing that has been conducted thus far. More samples with higher %S and total metal content and a wider range of net acid-generation potentials should be included in the testing program. In addition, an adequate number of ore samples (also based on mineralogic, alteration, and lithologic information) and pyritic tailings should be subjected to geochemical testing, especially to long-term leach testing.

3. Contaminant leaching potential

Nearly all the Pre-Tertiary samples and some Tertiary samples are potentially acid generating (PAG) (Figure 3). SRK Consulting shows only the 1:1 and 2:1 lines for NP:AP ratios on Figure 3, but ratios of 3:1 or even 4:1 are also used, with 3:1 being the most commonly used ratio (U.S. EPA, 2003; Maest et al., 2005). Using the 3:1 ratio line brings more of the Tertiary samples into the uncertain range (area between the 3:1 and 1:1 lines).

Although the EBD (PLP, 2011a) states that the tailings sampled to date are non-acid generating, Day and Linklater (2012) show that most of the PEZ tailings are PAG or uncertain and some of the PWZ tailings are PAG. HCTs and column tests on tailings should be run for longer periods of time because of the lower combined sulfide content and neutralization potential (Maest et al., 2005). In addition, a number of tailings samples from the Pebble West and East zones have elevated %S, antimony, arsenic, copper, nickel, lead, and zinc concentrations and low NP:AP ratios (many are 2 or lower, especially in PEZ) and therefore have elevated potential to produce acid and leach known aquatic and other toxins (PLP, 2011a; Tables 11-46 and 11-47). Although tailings supernatant metal concentrations were low, tailings were created without pH adjustment (PLP, 2011a, Section 11.7.2.3), which is not representative of operational conditions when tailings pH values would be 10 or higher. A bioassay on tailings supernatant is mentioned in Northern Dynasty Mines (2005), but results were not presented in the EBD.

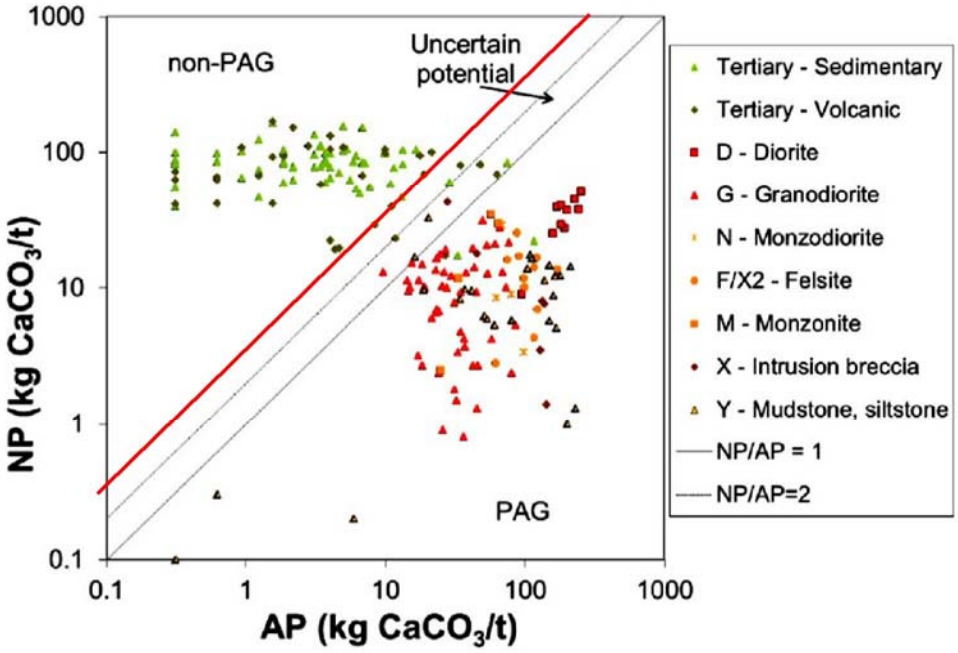

Figure 3. Acid-base accounting results for Pebble Tertiary (green) and Pre-Tertiary (red) rocks: NP and AP. The red line represents an NP:AP ratio of 3:1. This figure shows that all the Pre-Tertiary samples are PAG and some of the Tertiary samples are PAG or have an uncertain potential to generate acid.

Source: Day and Linklater, 2012. Slide 13.

When taken as a whole (PLP, 2011a), the short- and long-term leaching test results demonstrate that Pre-Tertiary samples have the highest copper leachate concentrations. As shown in Figure 4, lower leachate pH values produce higher copper concentrations. The majority of the leachate concentrations are more than 100 times higher than stream standards, indicating that leachate from host rocks, which would be present in tailings, waste rock, and the walls of the open pit and underground working, poses a substantial threat to aquatic life from copper toxicity.[4]

Unlike copper, selenium leachate concentrations were generally highest in Tertiary samples (PLP, 2011a), and the values are most elevated under neutral pH conditions, as shown in Figure 5. Selenium concentrations in leachate are up to 100 times higher than relevant stream standards for protection of aquatic life, suggesting that leachate from surrounding rock, which could be present in waste rock and the walls of the open pit and the underground mine, poses a substantial threat to aquatic life from selenium toxicity.

4. Aquatic life criteria are not directly relevant to leachate samples. The criteria are used to demonstrate the attenuation factors (dilution, treatment, removal) that would be needed if leachate ultimately mixed with surface waters.

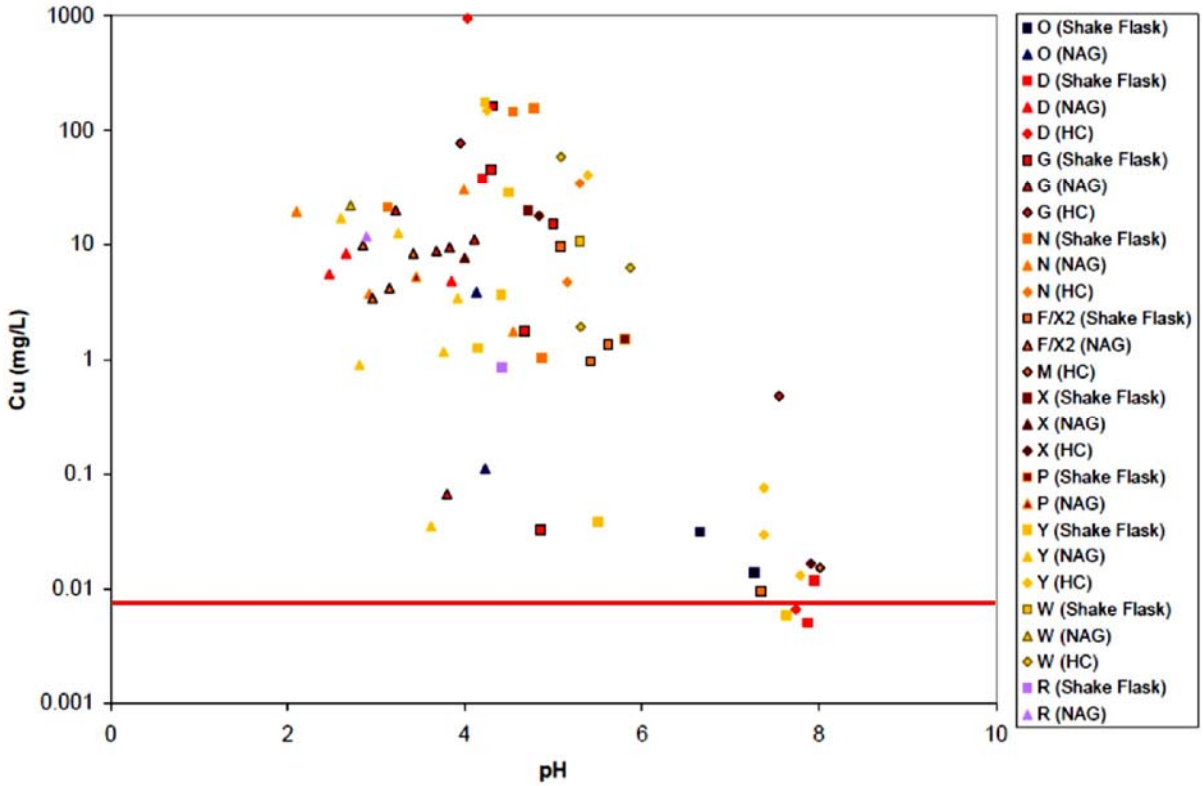

Figure 4. Copper concentrations as a function of pH in shake-flask extraction tests, NAG tests, and humidity cell leachates for Pre-Tertiary samples, PWZ. The red line represents the State of Alaska chronic total copper water quality criterion at 100 mg/L hardness (0.0093 mg/L Cu). Note that the vertical axis is logarithmic. Results from field barrel tests are not included. This figure shows that most characterized Pre-Tertiary PWZ materials are not environmentally benign because they leach copper concentrations in large excess of values known to cause toxicity to aquatic life over the long term, especially those with lower leachate pH values.

Source: PLP, 2011a; Figure 11-25.

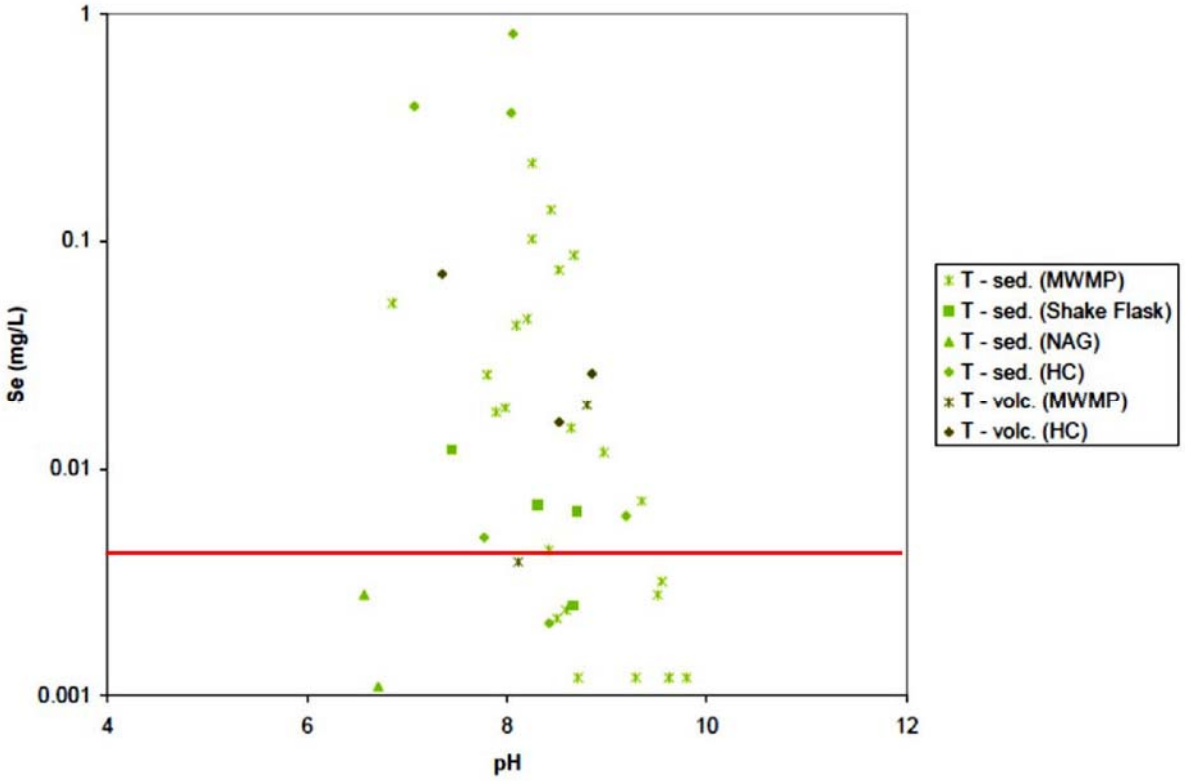

Figure 5. Selenium concentrations as a function of pH in shake-flask extraction tests, NAG tests, MWMP tests, and humidity cell leachates for Tertiary samples, PWZ. The red line represents State of Alaska chronic total recoverable selenium water quality criterion (0.005 mg/L). Note that the vertical axis is logarithmic. Results from field barrel tests are not included. This figure shows that the majority of the characterized Tertiary PWZ materials are not environmentally benign because they leach selenium concentrations in excess of values known to cause toxicity to aquatic life over the long term, especially those with neutral and higher leachate pH values.

Source: PLP, 2011a; Figure 11-42.

4. Time to onset of acid drainage

The time to onset of acid drainage for the mined Pebble deposit has implications for the management and environmental behavior of mined materials. If the waste rock, pit walls, and walls of the underground workings have a long delay before acid is formed, fewer mitigation measures (e.g., passivation of acid-producing rock) would need to be put in place during operation, treatment costs could be lower, and the effects on the environment from acid/metal-rich drainage could be reduced. The EBD estimates that the time to onset of acid drainage ranges from 1 to 78 years, depending on the NP:AP ratio, major rock type, and Pebble zone (PLP, 2011a, Table 11-42). The EBD (PLP, 2011a, Section 11.7.1.7) used the following final equation to calculate the time to onset of acid drainage:

$$t_{onset} = (NP_{eff}/AP)/k([NP/AP]_{crit}) \quad [1]$$

where t_{onset} is the time to onset of acid drainage, NP_{eff} is the effective neutralization potential, AP is the measured acid potential, k is the rate of sulfide oxidation, and NP/AP_{crit} is the lowest NP/AP ratio that will not form acid.

Sulfide oxidation rate: Average "stable" sulfate loading rates from the HCTs were used to estimate sulfide oxidation rates (k). However, the correlation between stable sulfate release rates and sulfide content is poor, (Table 11-41 of PLP, 2011a). PEZ and PWZ are lumped together in the EBD analysis, and the correlation r^2 values for Pre-Tertiary and Tertiary data are only 0.24 and 0.11, respectively (an r^2 value of 1.0 is perfect correlation). The HCT results show that, in general, rocks with higher %S values tend to have higher sulfate release rates (PLP, 2011a; Day and Linklater, 2012). However, neither %S nor sulfate loading rates correlate well with minimum pH values in the HCTs. Therefore, sulfate loading rate may not be the right measure to estimate time to onset of acid drainage. In addition, the use of mean stable rates ignores the importance of the formation and dissolution of secondary metal sulfate salts in the generation of acidic and metal-rich drainage. Although only two to three samples per year have been collected for the field barrel tests, it is apparent that metal and sulfate concentrations reflect seasonal cycles related to precipitation and snowmelt events, rather than showing a monotonic decline over time [see PLP, 2011a, Figure 11-29 (sulfate) and 11-30 (copper and zinc) for PWZ Pre-Tertiary barrel tests]. The majority of the HCT results also show a "first flush" (PLP, 2011a, Appendix 11G) with more elevated concentrations and lower pH values, whereby oxidation products build up in dry or cold periods and are flushed with the first rains or snowmelt, year after year. The use of average stable sulfate loading rates in the time to onset calculations ignores the natural cycles known to affect nearly all mine waste deposits and areas with natural acid drainage (Jambor et al., 2000; Maest et al., 2004).

Critical NP/AP: HCT leachate pH, calcium, magnesium, and sulfate values for Pre-Tertiary and Tertiary rock samples are used to estimate NP/AP_{crit}. Figure 11-51 (PLP, 2011a) was used to show that the critical NP:AP ratio for Pre-Tertiary samples is 1.6 because all samples with

average (Ca + Mg)/SO_4 molar ratios above 1.6 did not produce acidic HCT leachate. This molar ratio was then assumed to be the same as a NP/AP ratio of 1.6. One of the problems with this approach is that only one Pre-Tertiary HCT sample has an NP/AP ratio above 1.6 (PEZ sample 226293), and the remaining samples all have a ratio of 1.03 or lower. The NP/AP_{crit} does not work for the existing data, and HCTs on samples with a wider NP/AP ratio are needed.

Another problem with the approach is that there is not a good relationship between NP:AP ratio and leachate pH values in the HCTs. As shown in Figure 6 for Pre-Tertiary PWZ samples, and using a HCT leachate pH of 6 as the cutoff for acidic conditions, about half the HCT samples had minimum pH values below pH 6.0. This suggests, based on the testing conducted to date, that "critical NP:AP" cannot be used to separate rock types that will and will not produce acid. The same is true for %S vs. minimum HCT pH. No clear relationship between HCT pH and any more easily measured parameters are demonstrated in the EBD. These vexing results imply that more testing is needed on geochemical test units that incorporate alteration type – and that represent a wider range in NP:AP ratios and %S values – to try to find some relationship between long-term geochemical behavior and an easily measured parameter that can be used to effectively manage wastes in the field. As noted above, if such a relationship is not revealed, all mined materials may have to be managed as PAG or environmentally harmful.

Regardless of the theory and calculations associated with the time to onset of acid conditions, actual leach test results demonstrate that rapid leaching and acid formation has occurred over short timeframes in the tests on many of the samples [Appendices 11G (HCT graphs) and 11I (subaqueous column test graphs), and Figures 11-28–11-32 (barrel test graphs)]. Rocks that generate acid quickly are more difficult to manage protectively during mining operations. One management approach that has been shown in some cases to stop acid drainage is to submerge the mine waste under water (e.g., tailings and waste rock during and after mining, and walls of underground workings and open pits after mining). However, subaqueous leach test results in the EBD suggest that this management approach might not be effective at Pebble. Two Pre-Tertiary samples with only moderate sulfide contents (a granodiorite and a mudstone – the two most volumetrically important lithologies) went acidic quickly and leached high concentrations of cadmium, copper, nickel, and zinc, even under subaqueous conditions (Figure 7). The submerged samples that produced acid had done so before the tests began. Such results demonstrate that if acid generation starts, certain rocks can continue to generate acid and leach metals for extended periods of time, even when submerged.

5. Conclusions and recommendations

The static geochemical testing conducted for the EBD follow accepted and commonly used methods, and the results are generally of high quality. However, the kinetic testing program employed non-standard methodologies or non-standard modifications of accepted methodologies that were not well described.

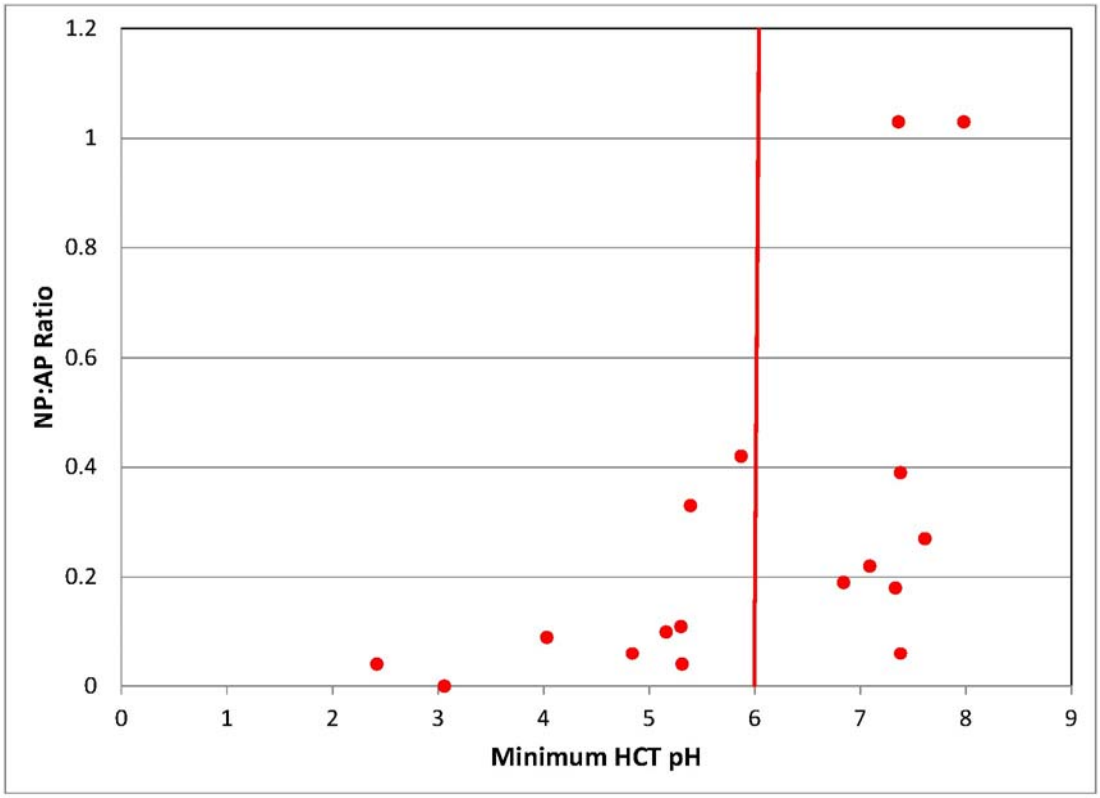

Figure 6. Relationship between NP:AP ratio and minimum pH value for Pre-Tertiary PWZ HCT samples. NP:AP ratio is not well correlated with minimum HCT pH. Only one HCT sample had a higher NP:AP ratio (not shown; in PEZ). Without more HCTs on samples with a wider range of NP:AP ratios, the "critical" NP:AP ratio cannot be established.

Data source: PLP, 2011a, Table 11-10 and Appendix 11C.

The representativeness of the geochemical testing program is lacking in the following areas: size of the studied resource is only half of the full resource; selection of geochemical test units did not consider hydrothermal alteration; the proportion of rock-type samples does not reflect the overall proportion in the ultimate pit surface or underground workings; the samples underestimate the acid generation and contaminant leaching potential of the deposit as a whole; and certain types of mined materials (ore and pyritic tailings) were not characterized at all (ore) or were not fully characterized (pyritic tailings). The extent of these issues severely limits the intended use of the data, especially for prediction of environmental behavior under mining and post-closure scenarios. New geochemical test units should be assigned using additional mineralogic and drill core information, and similar static and kinetic testing should be conducted on samples from these units.

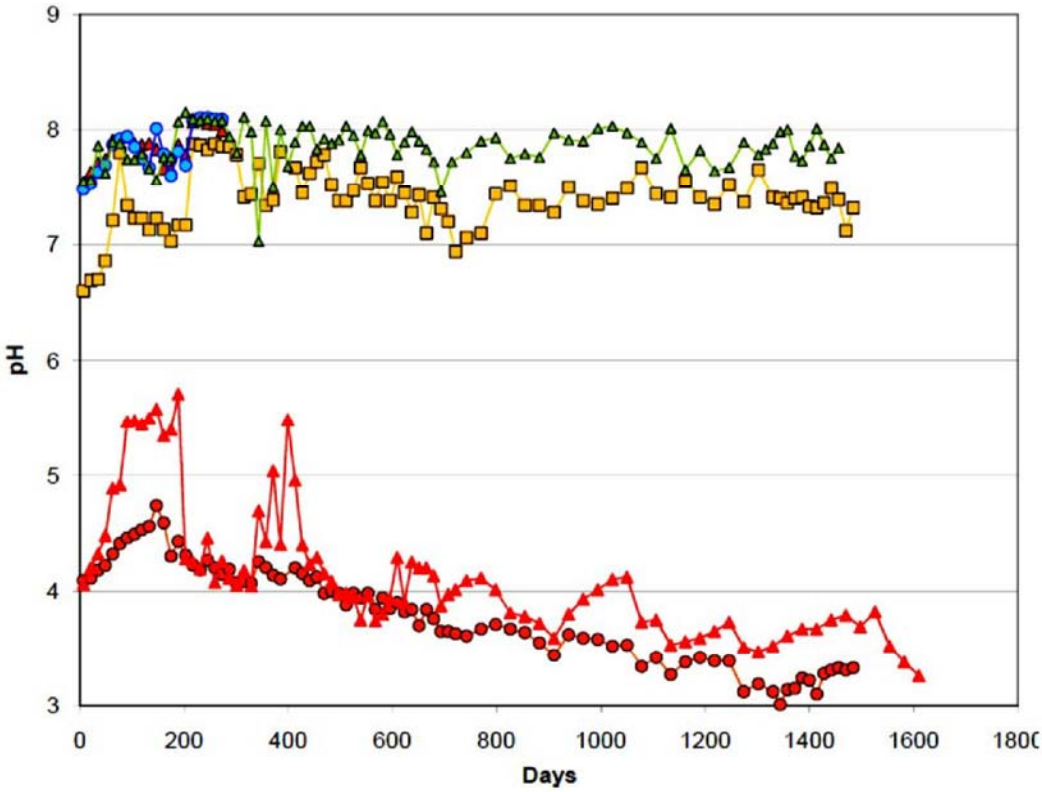

Figure 7. Leachate pH for PWZ Pre-Tertiary samples: Subaqueous columns. The two samples in red (the two most common rock types: granodiorite and mudstone) generated acidic leachate even though they were covered with water. These samples had become acidic before being submerged, suggesting that subaqueous disposal may not be effective at stopping acid drainage.

Source: PLP, 2011a, Appendix 11I, Chart 1.

Much of the leachate from Pre-Tertiary and Tertiary rocks exceeds stream water quality criteria by factors of one hundred or more. The highest copper leachate concentrations were produced from Pre-Tertiary rocks under acidic conditions, while Tertiary rocks leached elevated concentrations of selenium under neutral pH conditions. An important percentage of the samples released contaminants quickly, and weathered, mineralized Pre-Tertiary samples continued to leach acidity and metals for long periods of time, even under subaqueous conditions. These results, and the inability to find readily measurable indicator parameters for distinguishing PAG/metal leaching materials from more benign materials, indicate that mined material has the potential to release metals and acid at potentially environmentally harmful levels, many of the intended uses of the data cannot be realized, and an improved testing program is needed to better inform the management of mined material.

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