Rapid Seasonal Transition from Neutral to Acidic Drainage in a Waste Rock Test Pile at the Antamina Mine, Peru

Holly Peterson[1a], Roger Beckie[1b], Bevin Harrison[2], K. Ulrich Mayer[1c], and Leslie Smith[1d]

[1]The University of British Columbia, Vancouver, BC, CANADA,
[1a] hpeterso@eos.ubc.ca, [1b] rbeckie@eos.ubc.ca, [1c]umayer@eos.ubc.ca, [1d] lsmith@eos.ubc.ca
[2]Compañia Minera Antamina SA, Lima, PERU, bharrison@antamina.com

Abstract
Distinct seasonal changes were observed in the chemical composition of water draining from an experimental waste rock pile composed of intrusive material at the Antamina Mine in Peru. Effluent water pH was predominantly circumneutral (i.e. pH 7-8) and was characterized by low dissolved metal concentrations for the first two years following pile construction. In the middle of the third wet season, the pH dropped rapidly to pH 6.4, coinciding with significant increases in dissolved Cu and Zn concentrations from 3 mg/L to 65 mg/L and 20 mg/ L to 60 mg/ L, respectively. As expected, the decrease in pH also induced a dramatic decrease in dissolved Mo and As concentrations. Towards the end of the wet season pH rebounded to 6.7 and Cu and Zn concentrations again dropped to 4 mg/L and 41 mg/L, respectively, while Mo and As concentrations increased. Data from four basal collection lysimeters and smaller-scale field cells suggests that lower-pH water from isolated regions of highly reactive material strongly influences the overall chemical composition of the drainage from the test pile, even after dilution with higher-pH water infiltrating through much larger volumes of waste rock. Localized pH decreases are likely caused by carbonate depletion and exaggerated by longer residence times in fine-grained, highly reactive materials.

Key Words: Waste Rock, Geochemistry, Hydrology, Zinc, Copper, Transport

Introduction
The ability to predict a shift from neutral to acidic drainage is critical for mine planners, as is the prediction of the associated solute concentrations and mass loadings that are controlled largely by drainage pH. Concentrations of dissolved metals can vary significantly over slight pH ranges, which may dictate the water management decisions necessary to mitigate elevated solute concentrations and remove metals from the dissolved load. For example, neutral pH waters may tend to transport As, Mo, Se, and Sb while slightly acidic waters will carry Zn and Cu, and strongly acidic waters will transport Fe. In a system where effluent water from waste dumps has a variable pH, especially one that changes substantially on a seasonal basis, management options must be sufficiently robust to adapt to fluctuations in chemistry, and monitoring plans must be designed to detect rapid changes.

A variety of standard static and kinetic tools such as acid-base accounting (ABA), sequential leach and humidity cell tests can be used to estimate the potential for mine waste to produce acidic drainage. However, there are several variables which complicate the prediction of neutral and acidic drainage. Variables such as hydrology, oxygen availability, and heterogeneous mineralogy and particle size distributions are associated with the large-scale nature of the waste rock dumps and are difficult to reproduce in a laboratory setting (e.g., Smith and Beckie (2003), Lefebvre *et al.* (2001), Jambor (2003), Malmström *et al.* (2000)).

A research program to study hydrological, geochemical, and biological processes occurring in specific, isolated types of waste rock, as well as those same processes when multiple types of waste rock are placed in contact to one another, has been established at the Antamina mine in Ancash, Peru. The research project includes single and mixed waste rock experiments on multiple scales, ranging from µm-scale laboratory studies, to a set of 10 m high experimental waste rock piles in the field.

The Antamina experimental pile program provides an excellent opportunity to study the processes controlling neutral drainage in mine waste rock under field conditions. The Antamina polymetallic skarn deposit generates a large amount of limestone and marble waste rock that is not potentially net acid generating (NAG) with high carbonate buffering capacity, in addition to other carbonate and intrusive and skarn waste rock with a higher sulfide content, that can lead to acid production. The two waste dumps at Antamina are geochemically heterogeneous, with one dump containing predominantly NAG rock and the other containing higher percentages of potentially net acid generating (PAG) rock.

The high Andean climate (~4,300 masl) plays a significant role in the hydrological, geochemical, and biological activity in Antamina's waste dumps. The mine has a mean annual temperature of 5.6°C, average annual precipitation of about 1200 mm, and two distinct seasons: a wet season from about October through April, during which about 80% of annual precipitation falls, and a sunny dry season with warm days and cold nights from May through September. These shifts in precipitation play a major role in the internal water velocities – and therefore residence times and geochemical reaction rates – and effluent water flow rates and volumes of the Antamina waste rock piles.

One of the single rock type, large-scale experimental waste rock piles (Pile 2), constructed in 2007-2008, was developed to study the processes occurring in PAG waste rock that initially produce circumneutral effluent waters. Pile 2 is composed of intrusive rock with relatively high sulfide and low carbonate contents. Three wet seasons after pile construction, drainage from this 22,000 tonne, 36 m x 36 m x 10 m experimental test pile underwent a rapid transition from a near neutral pH (7.7) to slightly more acidic effluent water during the 2010-2011 wet season. The effluent water pH decreased about 1.3 pH units in two months, including about 0.9 pH units in just two weeks. During those same time periods dissolved copper and zinc concentrations increased significantly (Table 1). Substantial accumulation of a bright blue predominantly amorphous precipitate containing gypsum and malachite coincided with the pH drop (Figure 1). No accumulation of the precipitate has been observed in the field cell experiments or in the operating full-scale waste dumps, but a similar precipitate was observed during a laboratory experiment using material from Pile 2. The rapid changes in this field scale experimental waste rock pile provide valuable insight into how the combined influence of geochemical and hydrologic processes on pH-buffering processes, metal mobility and drainage quality may occur within full-scale waste rock piles.

Table 1. Summary of rapid aqueous compositional changes in Pile 2 basal lysimeter outflow during the 2010-2011 wet season.

Date	Field pH (pH unit)	Dissolved Cu (mg/l)	Dissolved Zn (mg/l)
23-Dec-2010	7.71	0.01	5.9
1-Feb-2011	7.25	2.6	21.4
17-Feb-2011	6.37	67.0	75.3
23-Jun-2011	6.64	4.3	41.9

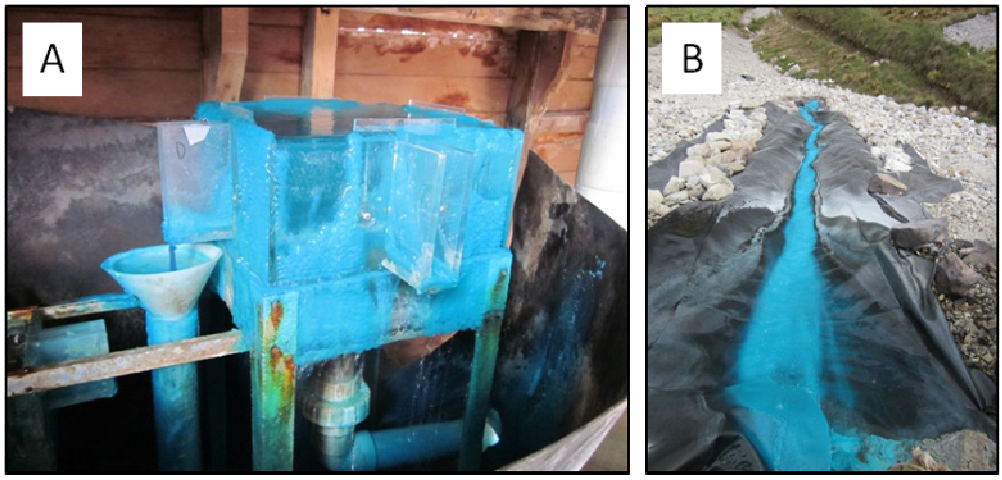

Figure 1. Accumulation of bright blue precipitate from effluent water (A) on flow gauge system and (B) in discharge areas.

Materials and Methods

Construction details and analytical techniques

Pile 2 was constructed of run-of-mine intrusive waste rock according to the methods outlined in Corazao Gallegos (2007) and Bay *et al.* (2009). The waste rock was placed on the pile in four separate phases, including a 1.5 m protective layer at the bottom of the pile and three sloped, end-dumped tipping phases (Figure 2). The waste rock in Pile 2 is considered by the Antamina classification system to be reactive (Class A). Rock for each tipping phase came from a distinct zone in the mine and therefore particle size distributions and mineralogy are varied. Field-scale humidity cells (field cells), which are about 1m tall and contain ~300 kg waste rock (<10 cm diameter) from each of the tipping phases were also initiated to capture ambient conditions on a smaller scale. Particle-size distributions for waste rock from each tipping phase were determined during construction.

All infiltration that migrates to the base of Pile 2 is collected in one of four zero-tension lysimeters. Lysimeters A, B, and C are each 4 m x 4 m and Lysimeter D is 36 m x 36 m (Figure 3). Drainage from the lysimeters is continuously monitored to quantify flow rates, and temperature and electric conductivity (EC) are measured at 30-minute intervals. This water is also sampled every one to two weeks and analyzed for cations, anions, and dissolved and total metals. Similar sampling procedures are followed for the field cells, except that flow rates are measured on a weekly basis. Instruments were also installed within the experimental pile to collect in-situ pore water and gas samples and measure EC, temperature, and volumetric moisture content.

Solid phase waste rock samples from Pile 2 were analyzed by ALS Labs in Lima, Peru. Analyses included solid phase trace metal concentrations using whole rock digestion and ICP-MS; acid-base accounting, including maximum potential acidity (MPA) and neutralization potential (NP) using the unmodified Sobek et al. (1978) method without siderite correction; and solid phase S and C by Leco. Precipitate samples were analyzed for trace metal concentrations using whole rock digestion and ICP-MS and solid phase S and C by Leco by ALS Labs in North Vancouver, BC, or Acme Labs in Vancouver, BC. All samples were also examined using a Philips Xl-30 Scanning electron microscope (SEM) fitted with a Princeton Gamma-Tech Energy-dispersive X-ray spectroscopy (EDS) system in the Department of Earth and Ocean Sciences at the University of British Columbia (UBC). Identification of mineral phases was performed by powder X-ray diffraction (XRD) on a Siemens D8000 Diffractometer. Qualitative identification of phases was carried out using EVA software, and quantitative analyses – i.e., the relative proportions of the minerals present – were determined using Rietveld refinement with Topas v.3.0 software.

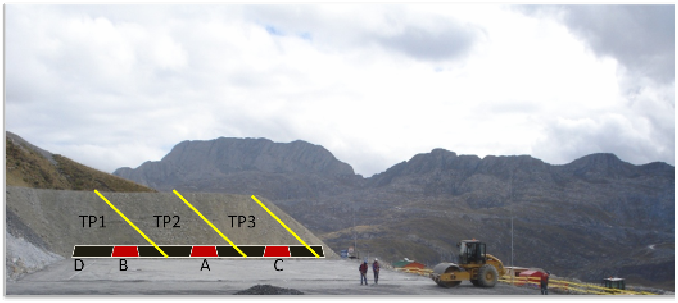

Figure 2. Photo of a test pile during construction, showing locations of tipping phases (TP1-TP3) and Lysimeters A-D.

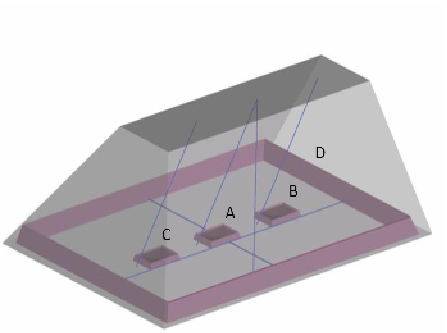

Figure 3. Three dimensional schematic showing locations of lysimeters A-D. Blue lines indicate approximate locations of instrumentation lines.

Solid phase elemental and mineralogical properties summary

The rock that comprises Pile 2 is classified as reactive Class A, as is all intrusive waste rock at Antamina. (See, e.g., Golder Associates (2010), Bay *et al.* (2009), and Hirsche *et al.*, (ICARD 2012) for details on Antamina's classification scheme.) Rocks from the individual tipping phases have variable solid phase elemental compositions (Table 2). The dominant minerals in the intrusive rock in Pile 2 as determined by XRD are quartz [SiO_2] orthoclase [$KAlSi_3O_8$] and plagioclase [$AlSi_3O_8$ – $CaAl_2Si_2O_8$] feldspars. The dominant sulfides are pyrite [FeS_2] and chalcopyrite [$CuFeS_2$] with trace molybdenite [MoS_2]. The only carbonate detected in some of the intrusive rock samples was siderite [$FeCO_3$] at weight percents below 1%. The garnet andradite [$Ca_3Fe_2(SiO_4)_3$] was abundant in sample 2-1B, but was not detected, or had a low abundance in the other samples. Micas, oxides, amphiboles, and diopsides are present in some of the samples at low percentages.

Table 2. Select solid phase analytical results for Pile 2 materials.

Field Cell ID	Tipping Phase	Associated Lysimeter	NP/MPA	S (%)	C (%)	As (ppm)	Cu (ppm)	Mo (ppm)	Zn (ppm)
2-0A	Protective layer	P2D	1.49	0.62	0.17	167	3340	265	187
2-1A	Tipping phase 1	P2B	1.90	0.20	0.15	54	612	429	33
2-1B	Tipping phase 1	P2B	0.06	4.26	0.09	21	1710	329	439
2-2A	Tipping phase 2	P2A	0.40	0.64	0.08	70	2680	393	186
2-3A	Tipping phase 3	P2C	0.14	1.56	0.05	228	7140	282	310

Particle size distributions

Particle size analysis was completed for each tipping phase. There is variability from tipping phase to tipping phase; samples 2-1B, 2-2A and 2-3A are finer-grained than samples 2-0A and 2-1A (Figure 4A). The average composition of Pile 2 is relatively fine-grained in comparison to the other large-scale test piles (Figure 4B), with an average D_{20} of 1mm (i.e., 20% of the material is finer than 1mm). Using a D_{20} cut-off of 2mm as the boundary between rock-like (macropore dominated) and soil-like (matrix dominated) flow behavior (e.g., Dawson *et al.*, (1998), Smith et al. (1995), Smith and Beckie (2003)) much of the rock in Pile 2 should exhibit soil-like behavior. Particles < 0.25 mm contribute most significantly to sulfide and silicate weathering (Strömberg and Banwart, 1999). Therefore, the relatively fine-grained nature of waste rock in Pile 2 has implications for infiltration rates of pore waters, residence time, sulfide oxidation rates and carbonate and silicate buffering capacities.

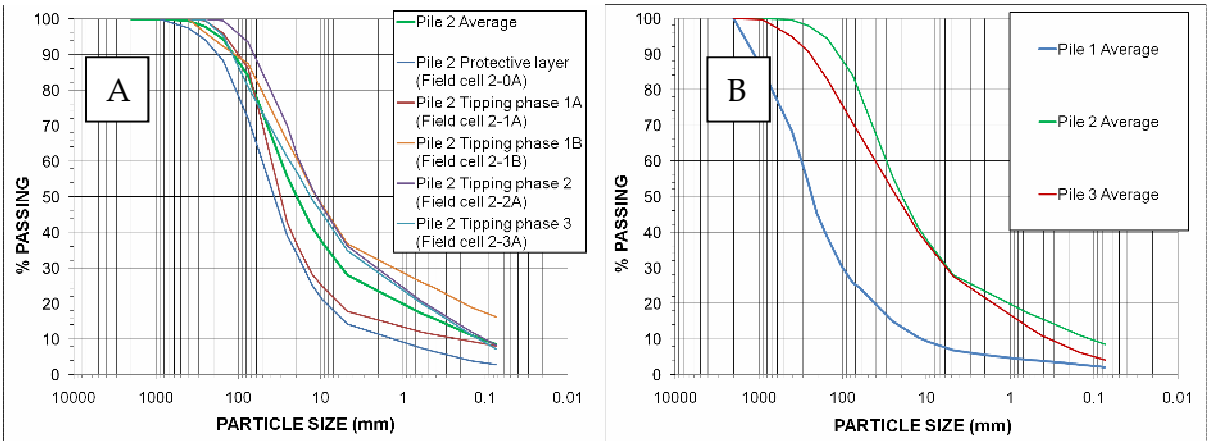

Figure 4. Particle size distributions for (A) Pile 2 individual tipping phases and (B) Piles 1-3 averages.

Results

Precipitation and Pile 2 Lysimeter D outflow

The wet and dry seasons at Antamina occur approximately from October to April and May to September, respectively. However, the rainy season sometimes shifts up to a month earlier or later or is shortened or lengthened, depending on the year. For this study, we consider a year to span from July 1 to June 30 so that an entire wet season is included in each year's dataset. Average annual precipitation varies around the Antamina mine site, and the data presented here are from the experimental piles location.

Volumetric fluxes from lysimeters (m^3/day) have been normalized to the total area of the lysimeter, and are therefore reported as specific discharge (mm/day) in order to compare directly with precipitation (mm/day). For example, 7 m^3/day, which is a typical volumetric flow from the pile during the wet season, is divided by the lysimeter area (1248m^2) to determine the specific discharge (5.6mm/day).

Cumulative annual precipitation in 2008-2009 was 1500 mm (Figure 5A), which is toward the upper end of historical precipitation data. Pile 2 Lysimeter D (P2D) flow, which equals about 97% of total pile flow, slowly increased from October dry season low flows (~0.2 mm/day) through December (~0.5 mm/day) before high flows began in January and continued through March (5 - 7 mm/day).

Precipitation was 1300 mm in 2009-2010 (Figure 5A). Minimum flows from P2D in October (~0.3 mm/day) increased more rapidly than in the previous year to 1 mm/day in November and 4 mm/day in December. Maximum flows ranged from 4 to 5 mm/day through March, with one high flow (7 mm/day) event in February.

In 2010-2011, which was the third full wet season since Pile 2 construction and the year in which the distinct pH shift was observed, cumulative precipitation was approximately 1300mm (Figure 5B). Lysimeter P2D flow increased from 0.2 mm/day in October to 1 mm/day in November and 1.8 mm/day in December. Flow then increased rapidly through January to reach maximum rates in February (6.2 mm/day), March (6.4 mm/day), and April (6.2 mm/day). During April 2011, a rapid accumulation of a solid-phase precipitate (see *Results: Solid-phase precipitate*) in the drainage pipes that convey water to the P2D flow meters caused a disruption in the flow measurements. The flow rate returned to its previous state after manual cleaning of the pipes.

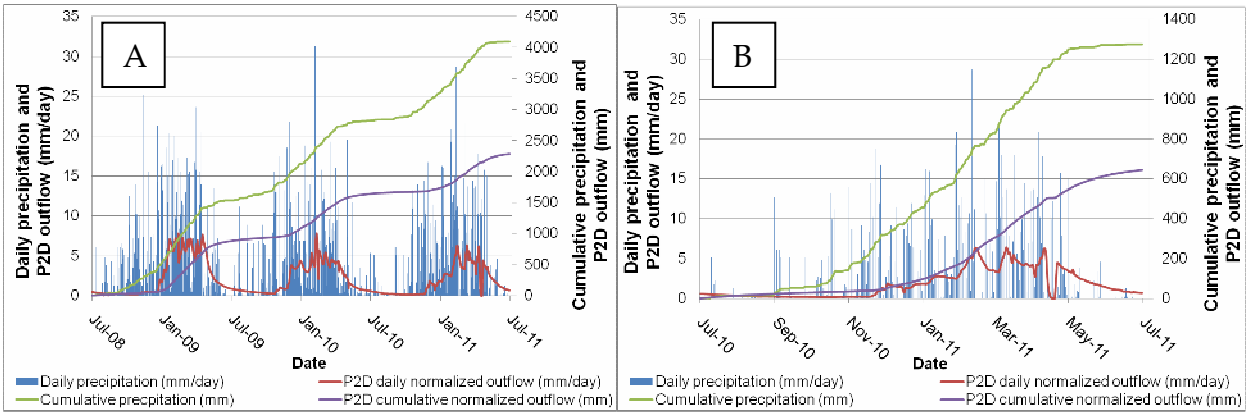

Figure 5. Daily and cumulative precipitation and P2D outflow for (A) 2008-2011 and (B) 2010-2011. Precipitation is reported as height of rain, and effluent flow as specific discharge, i.e. volumetric flux normalized to the
area of the lysimeter.

Effluent chemistry: Piles

Solute concentrations and pH from Pile 2 effluent fluctuate on an annual cycle with the precipitation and flow patterns described above (**Error! Reference source not found.**). The pH of P2D tends to be most alkaline under lowest flow conditions (October), and most acidic under highest flow conditions (March). Correspondingly, an observed direct relationship between dissolved Zn and Cu concentrations and flow was observed. Other elements such as Mo and As, which are generally less mobile in moderately acidic waters, increase to maximum concentrations during the first flush of each wet season, usually in November or December, and decrease to minimum concentrations toward the end of each wet season in May. These relationships started for most solutes in 2008-2009 and repeated in 2009-2010, and were enhanced greatly in 2010-2011.

In February 2011 the pH of P2D began to drop rapidly. In previous years, the pH of P2D was generally near pH 7.8 during lowest flow periods and usually dropped to about pH 7 over three months with the onset of the wet season high flow. In 2011 the pH dropped lower than in previous years and at a faster rate. The pH dropped from pH 7.7 to pH 6.4 between December and February, including a 0.9 pH unit drop from pH 7.3 to pH 6.4 over two weeks in February 2011.

Despite the pH dropping less than a unit lower than it had in previous years, concentrations of several dissolved metals rapidly increased significantly more in February 2011than in previous years. Notably, dissolved Cu concentrations increased from 0.01 mg/L in December 2010 to 67 mg/L in February 2011 (Table 1). Over the same time period, dissolved Zn concentrations increased from 5.9 mg/L to 75 mg/L, and dissolved SO_4 concentrations increased from 1500 mg/L to 1850 mg/L.

Other elements, Mo and As, which tended to exhibit lowest concentrations in May in previous years, showed sharp drops in March and April 2011, slightly later than the peaks in Cu, Zn, and Mn, but while the pH remained below pH 6.5. The 2010-2011 maximum Mo concentration (13 mg/L) was observed in December 2010 and the minimum (6.3 mg/L) in April 2011. The maximum concentration of As (0.051 mg/L) was reported in December 2010, and concentrations fell below the detection limit of 0.001 mg/L from late February to mid-April 2011.

As flow declined from the wet season, the pH of P2D increased to 6.7, and Cu and Zn concentrations decreased to 4.4 mg/L and 42 mg/L, respectively. The P2D Mo concentration increased to 9.2 mg/L and As increased to 0.025 mg/L. Sulfate remained around 2000 mg/L through June 2011.

The effluent chemistry of Pile 2 Lysimeter C (P2C), which is the lysimeter under the outer slope of the pile and represents tipping phase 3, follows similar seasonal trends as P2D, although often not to the same degree. Important differences to note for P2C in the 2010-2011 wet season include a minimum pH 6.6, a drastic spike in SO_4 to 5400mg/L, the limited mobility of dissolved Mo, and a smaller decrease of As than seen in P2D.

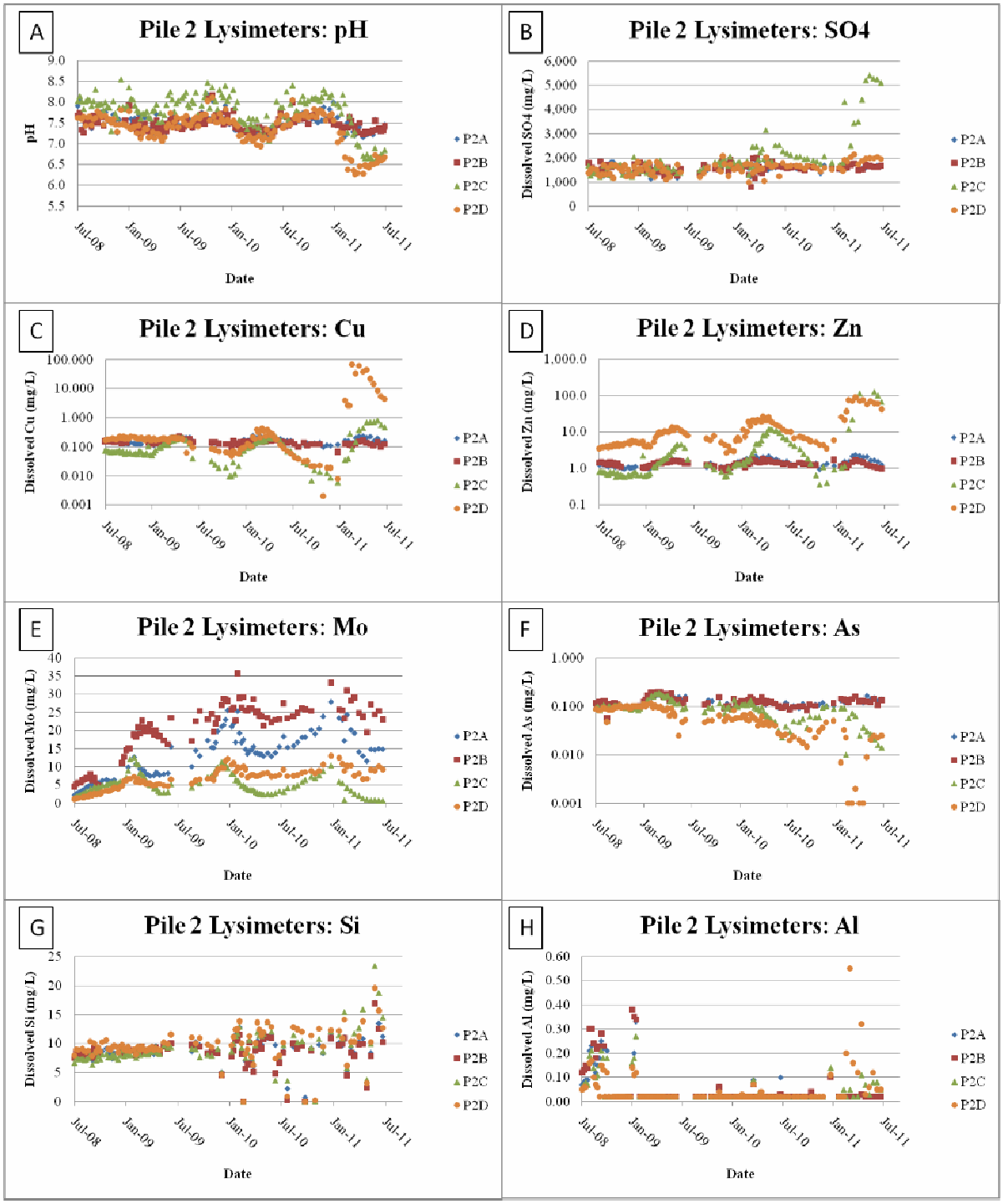

Figure 6. Aqueous geochemistry for Pile 2 lysimeters:
(A) pH (B) SO_4 (C) Cu (D) Zn (E) Mo (F) As (G) Si (H) Al

Effluent chemistry: Field cells

The field cells do not flow in the dry season. When the rainy season begins each year there is a flushing of solutes, generally resulting in maximum initial concentrations decreasing to minimum concentrations at the end of the wet season. Drainage pH for field cell 2-3A (corresponding to the material that is located above Lysimeter C) was consistently lower than the other field cells (**Error! Reference source not found.**). Drainage from this field cell also contains the highest Cu and Zn concentrations, and very low Mo and As concentrations. Three-year trends from all field cell data indicate that Cu and Si concentrations are generally increasing, SO_4 and Zn concentrations have reached an apparent steady state , and Mo and As concentrations are generally decreasing.

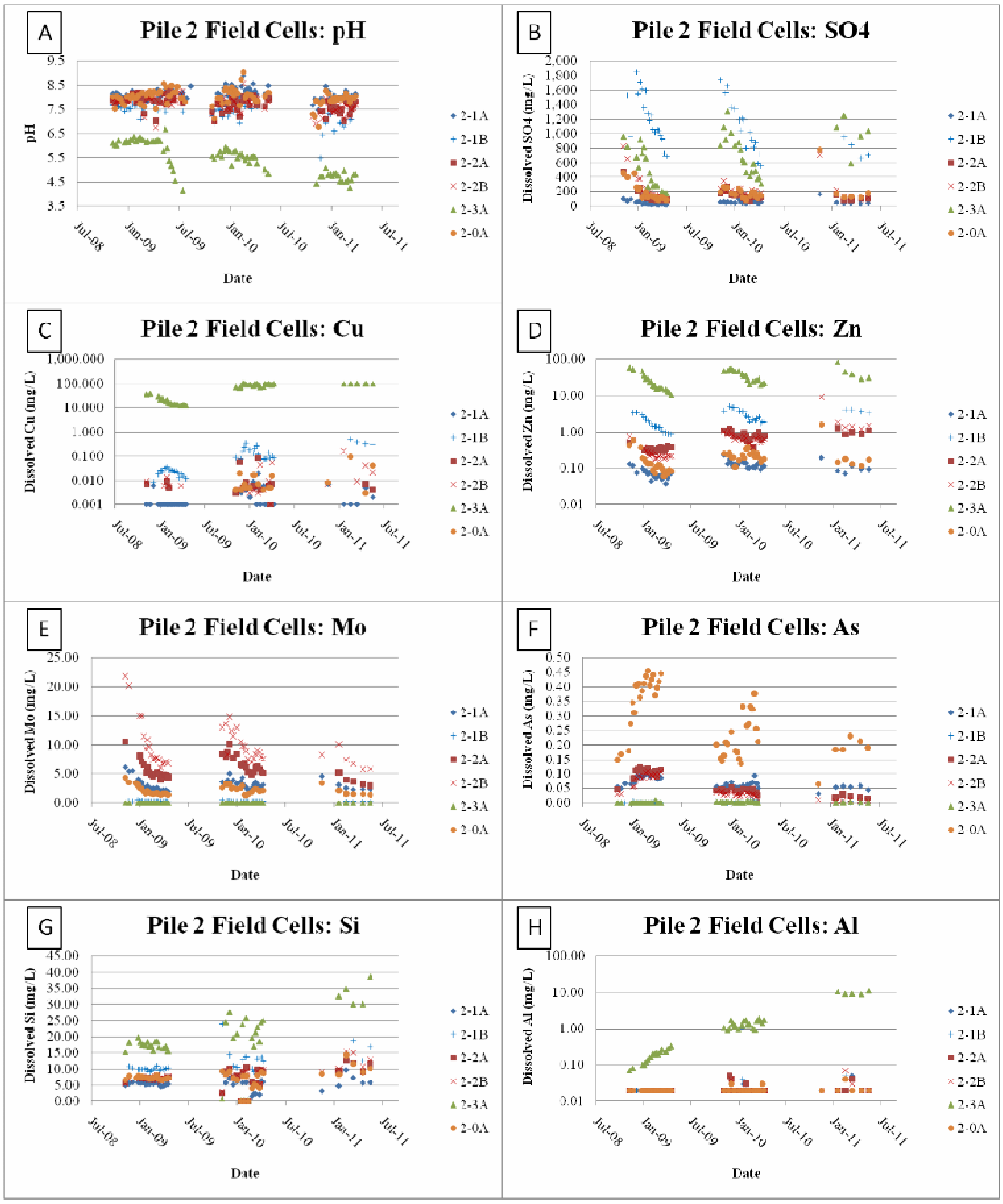

Figure 7. Aqueous geochemistry for Pile 2 field cells:
(A) pH (B) SO_4 (C) Cu (D) Zn (E) Mo (F) As (G) Si (H) Al

Solid-phase precipitate

A significant increase in accumulation of a solid-phase precipitate coincided with the pH drop and concentration and loading increases from the Pile 2 lysimeter D effluent. Prior to February 2011, small amounts of gypsum with low metal content had accumulated on the P2D outflow structures. After February 2011 large amounts of blue precipitate with a high metal content accumulated rapidly on flow gauges and in discharge areas (Figure 2; Table 3). Mineralogical analysis of the post-shift precipitate found that the precipitate is mostly amorphous material (73.8 %) and gypsum [$CaSO_4 \cdot 2H_2O$] (22.0%). Malachite [$Cu_2CO_3(OH)_2$] was also detected by XRD in small amounts (4.2%). Results from SEM and EDS analyses support the presence of the minerals detected by XRD. The dominant sulfate is gypsum, with little evidence of Cu-Zn sulfates. Copper was observed associated with spheres forming in the amorphous material, possibly as the carbonate malachite. The amorphous material contained variable amounts of Zn, Cu, Si, Al, Mn, Mg, S, and C, among other elements. A thin Cu-Zn-Si layer was observed on some surfaces of gypsum and the bulk amorphous material. Zinc was primarily found associated with Cu in the spheres or associated with Cu and Si in the surficial layer, but was also rarely associated with S.

Table 3. Selected solid phase analysis of P2D precipitate forming on outflow structures in August 2011.

Al (%)	As (ppm)	C (%)	Ca (%)	Cu (ppm)	Mn (ppm)	Mo (ppm)	Pb (ppm)	S (%)	Zn (ppm)
0.83	1182.33	1.02	6.07	>10000	4960	>4000	666	5.87	>10000

Discussion

A potential control on the decline in drainage pH during the 2010-2011 wet season is the depletion of carbonate neutralization capacity within isolated areas in the pile. Mineralogical and elemental analyses indicate that Pile 2 contains very minor (~1% maximum) amounts of carbonates. According to the ABA data for waste rock from Tipping Phase 3, which corresponds to lysimeter P2C and field cell 2-3A and has an NP/MPA of 0.14, carbonate depletion and acid generation was likely to occur over time. In general, silicate weathering may contribute to pH-buffering following the depletion of carbonate phases. Although this process is effective buffering in terms of moles of proton consumption, it is typically kinetically constrained, and therefore significantly slower than carbonate dissolution and sulfide oxidation. Previous studies (e.g., Jurjovec *et al.* (2002), Moncur *et al.* (2005)) have shown that silicate buffering occurs at significantly lower pH values than what is observed in Pile 2. Evidence of silicate dissolution was inferred based on increased dissolved Si concentrations in effluent from field cell 2-3A and lysimeters P2C and P2D, as well as the presence of Si in the precipitate. There is a possibility, then, that there are small zones within the pile where carbonate depletion and silicate weathering are occurring, and that low-pH water from those zones has a strong influence on the overall aqueous geochemistry of the outflow.

A second hypothesis concerning the distinct seasonal pH shift, which is exhibited clearly in the field cells, is a flushing of the water that remained in storage in the pile for the duration of the dry season. This "dry season" water would have a longer residence time than the component of the water in the wet season which migrates with a higher velocity resulting from macropore flow, increased water content, and ponding-induced increased heads and gradients. Seasonal flushing contributes to the yearly fluctuations in drainage chemistry since 2008, and is more dramatic during the 2010-2011 wet season.

Localized carbonate depletion and seasonal flushing of lower-pH water may be exaggerated by longer residence times in the finer-grained matrix. Indeed, water discharging from the pile during the 2010-2011 wet season may have had a 2- to 3-year or longer residence time, based upon preliminary tracer-study results. Again, the material in Tipping Phase 3 not only has lower carbonate content and higher sulfide and Cu content than most of the other tipping phases, but it also relatively fine-grained, increasing pore-water residence time. Ongoing monitoring of the tracer study and future chemistry data of the experimental waste rock piles and their associated field cells will lend additional insight into carbonate depletion, long-term seasonal flushing trends, and material residence times.

The similarities between the aqueous concentrations in lysimeters P2C and P2D – and indeed the strong differences between those lysimeters and the A and B lysimeters – suggest that one material type has a disproportionately strong influence on overall drainage chemistry. Tipping Phase 3 comprises only about one quarter of the pile by mass and volume, yet drainage chemistry for lysimeter P2D, which is representative of the entire pile, follows the effluent chemistry trends of lysimeter C very closely for pH, Zn and Cu. Field cell 2-3A also exhibits concentrations sometimes orders of magnitude higher than seen in the other field cells. There is a possibility that the sub-type of rock that is present in Field Cell 2-3A may not necessarily be located in the flow paths above P2C but is creating an acidic environment in certain areas within the pile. Strong spatial variations in pore gas composition in the pile (Singurindy *et al.,* ICARD 2012) also support the hypothesis that small amounts of reactive waste rock may dominate drainage chemistry of much larger areas despite dilution through the pile and at the base.

Variable mineralogy in waste rock also plays a role in drainage chemistry. For example, the presence of siderite as a main carbonate – rather than just calcite or dolomite – complicates the interpretation of net buffering capacity. Iron is released during siderite dissolution and then hydrolyzes, producing acid which counteracts the neutralization from carbonate dissolution. A second example of the importance of mineralogy is the differences in weathering rates and Cu released in chalcopyrite and bornite. The XRD analysis performed for this study has provided baseline knowledge of material mineralogy, and is being complemented by other techniques in order to examine both primary and secondary mineralogy in more detail.

Examples of these techniques that are being used to characterize Antamina minerals include mineral liberation analysis (MLA) (Blaskovich, ICARD 2012), optical microscopy, focused ion beam transmission electron microscopy (Dockrey 2010), synchrotron methods and extraction methods. Methods such as these can be used to better identify the types and quantities of carbonates in the system in order to refine the forms of NP in this type of waste rock and better characterize the quantities and types of sulfides.

The full-scale dumps at Antamina are still wetting and accumulating water into storage. Concentrations of metals and sulfate in seeps from those dumps also fluctuate with season, but have not shown rapid changes by orders of magnitude such as the ones seen in experimental Pile 2. On-going research is being conducted with laboratory scale experiments, field cells, experimental piles, and full-scale waste dumps to determine scaling factors that will assist in predictive water quality monitoring.

Modeling studies are underway to evaluate the geochemical processes responsible for the solid-phase precipitate. Future studies will determine the role of similar precipitates as attenuation mechanisms within the large scale dumps.

Conclusions

The distinct wet and dry seasons at Antamina support discrete periods of high and low water flow through the waste rock. These shifts in flow generally exhibited an inverse relationship with drainage pH, As and Mo concentrations, and a direct relationship with Cu and Zn concentrations. These shifts were gradually more pronounced each year, and after three years became more dramatic, significantly changing solute concentrations within weeks.

Reasons for the shifts may include depletion of carbonate phases, seasonal flushing, and variable residence times among flow paths. The study shows that small amounts of acidic water from reactive material may strongly influence overall outflow chemistry despite dilution with large volumes of less acidic water.

The findings of strong seasonal influences and impacts of reactive zones that have the ability to control the quality of large volumes of water both have important implications for water quality management. Rapid

shifts in pH and solute concentrations require flexibility in water management programs and monitoring vigilance, especially at the onset of rainy seasons. The results of this study in combination with other studies and the overall Antamina mine plan are being evaluated to implement appropriate measures. Scenarios are focused on investigating waste rock management strategies in the form of either complete waste segregation, as generally occurs now, or encapsulation and blending. Both scenarios have the objective of localizing the drainage produced from the highly reactive material types that are known to create "hot spots" and minimize the effect of these "hot spots" downstream.

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Acronyms

ABA	Acid base accounting
EDS	Energy-dispersive X-ray spectroscopy (EDS)
NP/MPA	Neutralization Potential/Maximum Potential Acidity
NAG	Not potentially net acid generating
P2C	Pile 2, Lysimeter C
P2D	Pile 2, Lysimeter D
PAG	Potentially net acid generating
SEM	Scanning electron microscope

UBC	The University of British Columbia
XRD	X-ray diffraction