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Environmental Geochemistry of an Epigenetic Pb-Zn-Ag deposit at the Abandoned Cecilia mine, Puno region, Peru

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ABSTRACT

The abandoned Cecilia Pb-Zn-Ag mine is located at the headwaters of the Lake Titicaca watershed in the Altiplano of Peru. The site is characterized by three months of high precipitation and nine months of limited precipitation. The environmental geochemical characterization of the abandoned mine was done to evaluate environmental risks at the site from mine wastes and mine drainage, and their potential for downstream impacts on water quality in Lake Titicaca.

The approach included sampling of mine waste, water, and sediment. Composite mine waste samples were collected from six main piles (four tailings, two waste rock). The surface water was collected from (1) drainage from mine portals; (2) the Cecilia and Crucero rivers upstream of mine influences; (3) the impacted reach of the Cecilia River down to its confluence with the Crucero River; and (4) the Crucero River, which receives drainage from the Cecilia River. Sampling in the dry season did not identify seeps from the waste rock or tailings piles.

This study documents the capacity of the site to generate acid mine drainage from the mine waste and underground workings. Mine waste has elevated concentrations of As (up to 883 mg/kg), Cu (up to 20,106 mg/kg), Pb (up to 16,716 mg/kg), and Zn (up to 11,937 mg/kg). Results for dissolved concentrations from leaching experiments on mine waste samples showed high leachability for As (0.001 to 0.95 mg/L), Cu (0.01 to 57.34 mg/L), Cd (0.001 to 1.13 mg/L), Fe (0.42 to 785 mg/L), Zn (0.01 to 91 mg/L), and Mn (0.05 to 279 mg/L) with an acidic pH (2.5 to 6.0). Water chemistry at the site varied on the basis of water type. The Cecilia and Crucero rivers had neutral pH and low concentrations of metals upstream of mine influences. In contrast, samples collected at the mine portal were highly acidic (pH 1.4 to 3.7) with high dissolved concentrations of Fe (up to 4,720 mg/L), Al (up to 400 mg/L), sulfate (up to 19,428 mg/L), As (up to 5.92 mg/L), Cd (up to 9.84 mg/L), Cu (up to 1.56 mg/L), Pb (up to 1.95 mg/L), and Zn (up to 4,065 mg/L), causing an increase in metal concentrations in the river downstream after mixing. Carbonate rocks in the watershed produce alkaline waters that neutralize acid drainage prior to its confluence with the Crucero River. Proposed remediation methods include capping mine waste to limit contact with rainwater and passive treatment of mine portal drainage.

Keywords: water quality, abandoned mine, dissolved metals, mine tailings, mine drainage, remediation

1.0.   INTRODUCTION

The Andes region is one of the richest orogenic belts in terms of metallic ores and several Andean countries are among the top mining countries in the world, either in production or in geologic reserves, of Sb, Ba, Be, Bi, B, Cu, In, Pb, Mo, nitrates, Pt, Re, Se, Ag, Te, Sn, W, and Zn (Petersen, 1977; Oyarzún, 2000; Fontboté, 2018). Additionally, the Altiplano-Puna plateau is a unique environment; its main distinguishing characteristics include a high elevation above 3,000 m and limited amounts of precipitation with strong seasonal variations (Tapia et al., 2022).

Geochemical-based environmental studies were developed in the Peruvian Andes to investigate influences of local climate on acid mine drainage (AMD) formation in a setting with high sulfide-content mine waste. During the dry winter season, high evaporation led to the formation of metal-enriched, highly soluble efflorescent salts at the base of a waste rock dump. During the wet summer season, rain events cause the dissolution of most efflorescent salts producing acid solutions rich in Fe, Mn, Zn, Cu, Cd, As, and S (Smuda et al., 2007; Murray et al., 2021; Lima et al., 2021). The goal

of this paper is to evaluate environmental risks from mine wastes and mine drainage at the Cecilia abandoned mine site and their potential for downstream impacts on water quality within the Lake Titicaca watershed. This information will guide the selection of remediation approaches.

1.1. Regional Geology

The Cecilia mine (14.49469°S; 69.83843°W) is located in the Altiplano of the Cordillera Oriental in southeastern Peru. The region is dominated by a succession of Ordovician to Permian sedimentary rocks. The area has experienced Permian to Triassic peraluminous granitic intrusive activity and Tertiary rhyolitic volcanism (Clark et al., 1990). Structurally, the area is dominated by an anticline (N65°E) and a syncline (S25°W) (Orbegozo and González, 1982). The area is cut by four fault systems trending N10°-15°E, N20°-30°W, N50°-75°W, and N70°-80°E that display evidence for brittle to ductile deformation (Chapoñán, 1994).

The Cecilia orebody is hosted by quartz arenites of the Mississippian Ambo Group near the contact with the overlying Tarma and Copacabana Groups (Clark et al., 1990). The principal geologic units exposed in the Cecilia mine are the Ambo Group – the host of the Cecilia orebody, the Tarma Group, and the Copacabana Group (Girard, 1984). The Ambo Group consists of buff-colored sandstones and intercalated conglomeratic and coal-bearing horizons. The rocks are continental in origin and were deposited in the Mississippian (Lower Carboniferous). The Tarma Group comprises black to dark gray bituminous shales and interbedded, lenticular, dark gray limestones deposited in the Pennsylvanian (Upper Carboniferous). In the Cecilia mine, they have been described as buff to gray, quartzosic-to-feldspathic, carbonaceous sandstones; these are flat-lying, planar-bedded sandstones that become intercalated with black, carbonaceous-rich shales near the top of the section, where they are overlain by massive gray limestone of the Lower Permian Copacabana Group (Girard, 1984). Both the Tarma Group and the Copacabana Group are noteworthy because they represent carbonate rocks in the headwaters of the Cecilia River watershed. No igneous rocks are found in the immediate vicinity of the mine, but an outlier of the Miocene Picotani volcanic field is found 1.5 km to the southeast of the mine (Clark et al., 1990).

1.2. Economic Geology

Cecilia is a manto-style epithermal Pb-Zn-Ag(-Sn) deposit consisting of stratabound veins (Clark et al., 1990). The ore mineralogy is dominated by massive accumulations of sphalerite, galena, pyrite, marcasite replacing pyrrhotite, chalcopyrite, and stannite; quartz is the main gangue mineral. The alteration was predominantly localized silicification and kaolinization (Girard, 1984; Chapoñán, 1994). The manto system has a strike length of approximately 600 m. It reaches a maximum width of 12 m. The vein splits into another vein at depth, with a 3-4 m width. The stratiform and stratabound bodies are hosted by the sandstone intercalated with carbonaceous shales. The mineralization occurred as thin lenses in the interbedded shales, as irregular veinlets cutting the sandstone, as dissemination, or concentrations in troughs or cross-beds that are organic rich, and in vertical fractures (Girard, 1984).

The mine was initially worked in colonial times for Pb and Ag. In 1972, a concentrator plant was installed, and the mine life was extended until its closure in 1985 (Orbegozo and González, 1982; Clark et al., 1990). The mine produced 1.2 million tonnes of ore with grades of 6.8% Zn, 2.68% Pb, and 73 g/t Ag (Clark et al., 1990). At present, the mine is abandoned.

1.3. Climatic and hydrologic setting

The study area has a semi-dry and semi-cold climate (SENAMHI, 2017). There is a meteorological station located near the study area in Crucero. It receives on average 645.7 mm of precipitation per year, with average daily temperatures ranging from a low of -5 °C in winter to a high of 16.5 °C in summer (SENAMHI, 2017); the mean annual temperature is 9.6 °C (ANA, 2010). The highest monthly rainfall, which occurs in the summer is 133.3 mm (December), and the lowest monthly rainfall, which occurs in the winter is 5.3 mm (July). Most (78 %) of the precipitation occurs from November to April and 66 % of evapotranspiration occurs from May to July. The data used in the study area were obtained from the PISCO (Peruvian Interpolated data of the SENAMHI's

Climatological and Hydrological Observations) database. The precipitation shown in Figure 1 is the average of the three stations surrounding the Cecilia mine: Muñani, Azangaro, and Progreso.
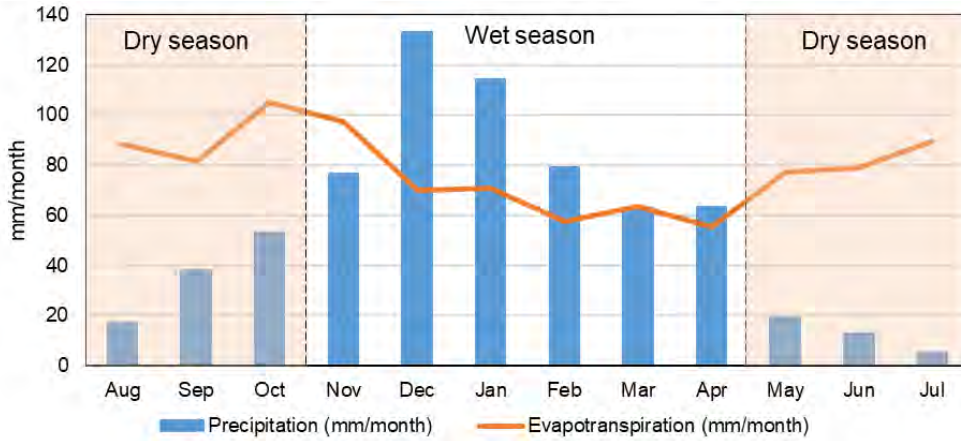
- **Figure 7. Average annual precipitation and evapotranspiration from three stations (Muñani, Azangaro, and Progreso) surrounding the Cecilia mine.**

The Cecilia mine is in the Alto Azangaro sub-basin (Figure 2). The river that is directly influenced by the mine is the Cecilia River, which drains in a northeastern direction. The catchment area of the Cecilia River is 18 km^2. The Cecilia River empties into the Crucero River, which flows to the northwest and eventually empties into Lake Titicaca, 275 km downstream.
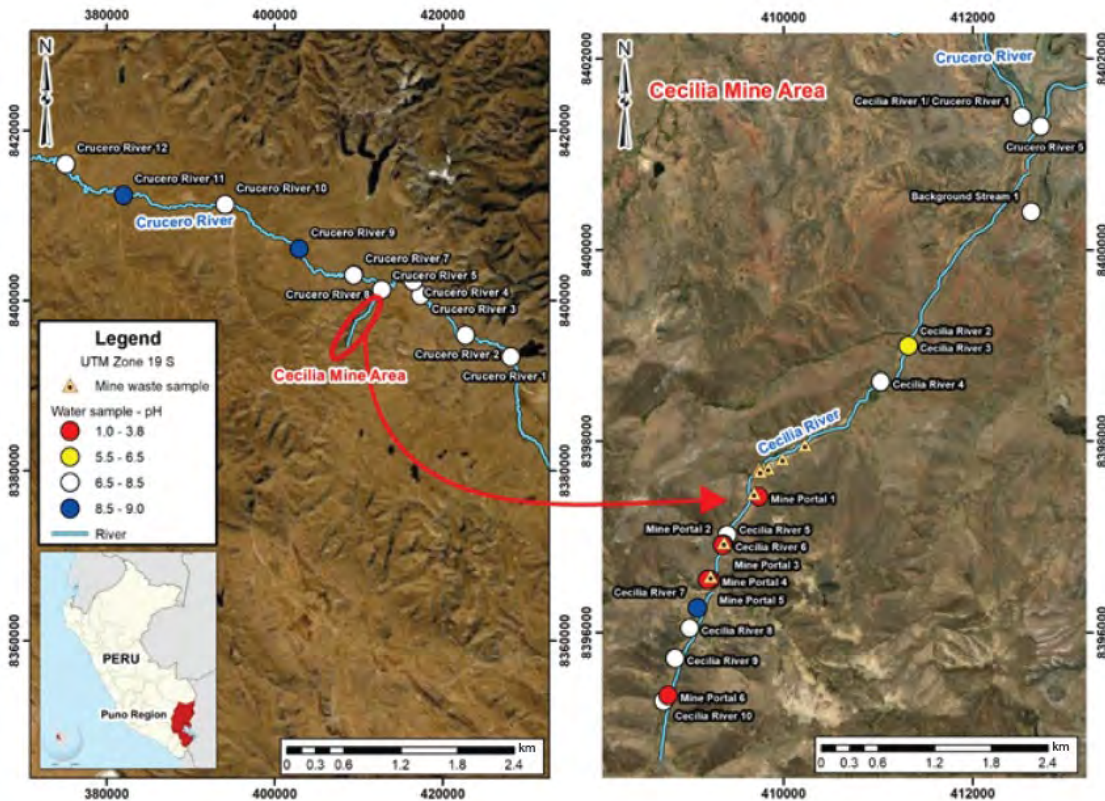

Figure 2. Map showing sampling sites in the Crucero River watershed. The inset map shows details within the Cecilia abandoned mine area. Coordinates are UTM.

2.0.   METHODOLOGY

This section provides an overview of geochemical characterization undertaken on mine waste samples from six sites (four tailings, two waste rock) and on water samples (mine portal drainage, surface water).

2.1. Mine waste samples

Surficial tailings and waste rock (upper 5 cm) were sampled by collecting 30 subsample composites from six main piles that were deposited next to the Cecilia River (Figure 3). Composited sediment samples were collected at various locations along the Cecilia River. Samples of waste rock, tailings and sediments were analyzed for major, minor and trace elements, by inductively coupled plasma-mass spectrometry (ICP-MS), and inductively coupled optical emission spectroscopy (ICP-OES). The mineralogy was determined by optical microscopy, powder X-ray diffraction (XRD), and scanning electron microscopy (SEM). Quantitative XRD was accomplished using the reference intensity ratio method; the amorphous content was estimated by comparing peak and background counts. The acid-generating potential and acid-neutralizing potential of mine waste were determined by Acid-Base Accounting using the procedures of Sobek et al. (1978). The Synthetic Precipitation Leaching Procedure (SPLP) (U.S. EPA Method 1312) (USEPA, 1994) was used to determine the leachability of trace elements.

Figure 3. Photographs of tailings deposit (left) and white to yellow copiapite efflorescence on the surface of tailings (right). The ledge of tailings in the lower right of the left photo is approximately 0.5 m in height.

2.2. Water samples

Parameters measured at the time of collection included water temperature, pH, specific conductance, and oxidation-reduction potential (ORP) (Table 1). Alkalinity was determined by Gran titration. Cation concentrations were determined by ICP-OES and ICP-MS on both filtered and unfiltered splits. Sulfate and chloride concentrations were determined by ion chromatography.

The surface water was classified in four groups: (1) mine portal drainage; (2) the Cecilia River, which receives mine-influenced water; (3) the Crucero River downstream of its confluence with the impaired Cecilia River; and (4) upstream reaches of the unimpaired Cecilia and Crucero rivers, which serve as background sites (Figure 4). Another background stream sample was taken from a small tributary to the Cecilia River. Because sampling was done in the dry season, no seeps were identified from the bases of the waste rock and tailings piles.

Figure 4. Pictures taken in June 2015 of Cecilia River near sample Cecilia River 2 (left) and a mine portal 4 (right).

- **Table 4. Water sample descriptions**

Sample	Coordinates (UTM)		Date	Field parameters				
	East	**North**		**pH**	**T(°C)**	**SC (µS/cm)**	**TDS (mg/L)**	**ORP (Mv)**
Cecilia River 2	411318	8399001	6/8/15	5.86	12.00	1080.0	540	102
Cecilia River 3	411318	8399001	6/8/15	5.86	12.00	1080.0	540	102
Cecilia River 4	411029	8398623	8/6/15	6.65	12.90	660.0	330	-65
Cecilia River 5	409403	8397022	8/6/15	6.91	9.70	630.0	320	-97
Cecilia River 6	409364	8396923	2/6/14	6.84	11.70	833.0	303	NM
Cecilia River 7	409087	8396259	2/6/14	8.70	13.00	588.0	287	NM
Cecilia River 8	409005	8396048	8/6/15	8.35	6.10	420.0	210	70
Cecilia River 9	408851	8395732	2/6/14	7.93	11.70	621.0	306	NM
Cecilia River 10	408727	8395284	6/8/15	8.26	9.27	500.0	250	368
Crucero River 1	428145	8393421	9/6/15	8.16	8.20	270.0	140	-12
Crucero River 2	422731	8395982	9/6/15	8.13	9.90	260.0	130	64
Crucero River 3	417372	8400657	5/6/14	8.50	10.00	271.8	135	NM
Crucero River 4	416496	8402329	9/6/15	8.18	10.70	230.0	120	80
Crucero River 5	412722	8401292	8/6/15	7.95	12.80	500.0	250	128
Crucero River 7	409437	8403042	9/6/15	8.15	10.80	260.0	130	92
Crucero River 8	409422	8403030	5/6/14	8.37	9.50	371.5	186	NM
Crucero River 9	402950	8406118	5/6/14	8.58	13.30	405.9	201	NM
Crucero River 10	394071	8411336	9/6/15	8.23	13.20	310.0	150	111
Crucero River 11	381996	8412454	5/6/14	8.71	13.90	403.3	199	NM
Crucero River 12	375099	8416083	9/6/15	8.19	11.60	350.0	170	64
Cecilia River 1/ Crucero River 1	412522	8401398	2/6/14	7.85	14.50	325.5	161	NM
Mine Portal 1	409738	8397423	6/8/15	2.76	12.61	550.0	275	516
Mine Portal 2	409356	8396924	8/6/15	3.70	11.90	3540.0	1770	273
Mine Portal 3	409354	8396918	6/8/15	1.74	14.66	3740.0	1870	272
Mine Portal 4	409223	8396556	8/6/15	1.39	13.90	16740.0	8350	385
Mine Portal 5	409195	8396554	6/8/15	1.78	7.16	15080.0	75400	373
Mine Portal 6	408780	8395345	6/8/15	3.73	6.11	1410.0	705	367
Background Stream 1	412620	8400400	8/6/15	7.65	14.50	350.0	180	24

Note: NM: Not measured

2.3.   Site inspection

Surface water samples were collected throughout the Cecilia River and Crucero River watersheds (Figure 2). The distance between the lowermost mine waste pile and the confluence of the Cecilia River with the Crucero River is approximately 2 km.

3.0.   RESULTS
3.1.   Mine waste samples
3.1.1.   Mineralogy

The main minerals, as determined by XRD analysis, are quartz, pyrite, gypsum, muscovite, kaolinite, jarosite, and chlorite, along with minor phases of albite, montmorillonite, chlorite, anhydrite, and goethite (Table 2). Some minerals occurred as major phases in one sample, but as minor phases in

others, for example albite. Gypsum is a common secondary mineral found throughout the area in mine waste samples. Other minerals related to acid mine drainage were found in all samples, mainly pyrite (0.4-23 wt.%) and native sulfur (2-5 wt.%).

- **Table 5. Mineral composition of samples determined by quantitative XRD analysis as weight %**

Samples	Quartz	Muscovite	Kaolinite	Albite	Montmorillonite	Chlorite	Gypsum	Anhydrite	Natrojarosite	Gibbsite	Jarosite	Copiapite	Calcite	Pyrite	Sulfur	Halite	Amorphous
GR1-RV1	57	5	2				11	1						23			
GR2-RV1	53	4	1				32		2					5			
GR3-RV1	47	2	2				17		6	3				21			
F1-RV1	80		4								6			<1			
F2-RV1	81	5	3	1	1		3				6					1	
F3-RV1	88	3	2	<1	1		2				3						
C1-RV1	76	1	1	1	1		7				6			4			
C3-RV3	63	6	1				14				6			1	5		
C4-RV4	60	1	1				23				5			3	2		
C5-RV5	39	3	1		1		49				4			1			
C6-RV6	53	6	2		1	1	32				5			1			
SED-CEC-01	38	5	8														48
SED-CEC-02	71	7	13	4									3				
PP1-RV-1	11						4					29				5	32

Sample explanation: GR coarse tailings grab sample; F fine tailings grab sample; C composited sample of tailings or waste rock; SED sediment sample; PP precipitate sample near mine portal.

One priority of this study was to investigate the distribution of minerals that define risks to human health and the environment. The presence of galena at the site is noteworthy. This mineral was identified in our samples (Figure 5), albeit in concentrations below the detection limit for quantitative XRD (< 1 wt. %). SEM reveals that galena is commonly rimmed by the secondary mineral anglesite ($PbSO_4$), a form that is less bioavailable than cerussite ($PbCO_3$), which is commonly found as a weathering product of galena in carbonate-rich settings (Plumlee et al., 2006).
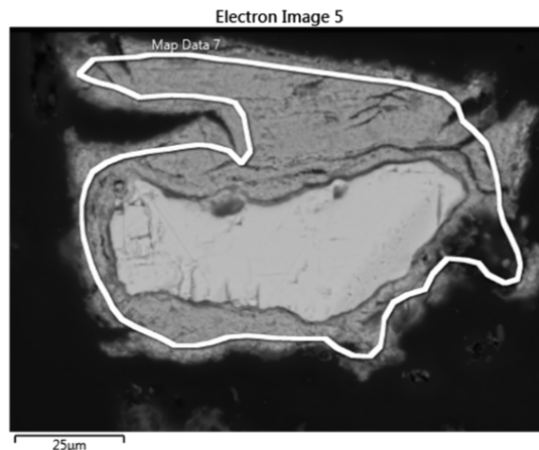

- *Figure 5. SEM back-scattered electron photomicrograph of galena rimmed by anglesite (Sample C4-RV4).*

3.1.2. Acid-Base Accounting

Oxidation of sulfide minerals, especially pyrite, is the major factor in acid production and subsequent release of potentially toxic elements that are generally dissolved in low-pH fluids. However, the presence of considerable amounts of carbonate and, to lesser extent, certain silicates such as feldspars and aluminosilicates may result in some neutralization of acid. There is a strong correlation between total sulfur and sulfide sulfur in our samples, which reflects the presence of pyrite as the main sulfur-bearing phase in many samples (Figure 6).

The acid-generating potential (AP) values ranged from nearly zero up to 600 kg CaCO$_3$/t, whereas the acid-neutralizing potential (NP) values were slightly negative owing to the high sulfide content of the samples (Figure 6). Thus, our samples are all classified as potentially acid-generating.
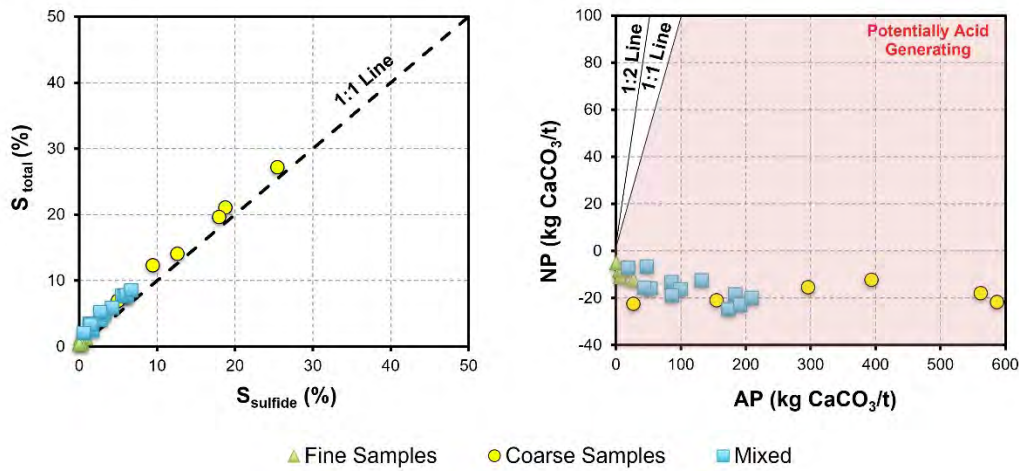
- Figure 6. Acid-base accounting characteristics of mine waste samples. The nearly 1:1 correlation of total S and sulfide S (left) demonstrates that most S is sulfidic. The acid-generating potential (AP) vs acid-neutralizing potential (NP) characteristics (right) show that all samples are strongly acid- generating, as shown by the pink field with NP/AP < 1.

3.1.3. Metal content in the mine waste

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- Trace elements in the mine waste are dominated by Pb, Zn, and Cu, which reflect the primary mineralogy of the ores that were processed on-site. Some potentially toxic elements, such as As, Hg, Cd, and Sb, also occur in substantial amounts. The summary statistics for the geochemistry of mine waste samples are presented in Table 3.

- Table 6. Summary statistics of elemental concentrations in mine waste samples

Elements	Unit	Tailing Samples (n=22)			Mine Waste Sample (n=1)
		Average	Minimum	Maximum	
Al	wt. %	2.0	0.04	6.7	0.2
Sb	mg/kg	17.9	0.4	60.2	653
As	mg/kg	273.0	43.5	883.0	193
Ba	mg/kg	107.9	4.9	420.0	78.37
Be	mg/kg	1.2	0.1	2.9	0.23
Bi	mg/kg	0.7	0.1	1.7	--
Cd	mg/kg	8.6	0.2	82.0	4.727
Ca	mg/kg	6975.0	285.9	14400.0	--
Co	mg/kg	2.0	0.2	9.0	1.23
Cu	mg/kg	2927.1	7.9	20106.4	66.9
Cr	mg/kg	14.1	0.6	47.0	3.74
Sn	mg/kg	3.7	0.1	9.4	--
Sr	mg/kg	28.8	3.8	84.8	--
Fe	wt. %	4.9	1.1	15.7	7.78
Li	mg/kg	241.8	117.0	429.0	--
Mg	wt. %	0.1	0.003	0.3	--
Mn	mg/kg	124.6	8.8	556.9	134
Hg	mg/kg	0.5	0.02	1.2	6.78
Mo	mg/kg	1.3	0.3	2.6	1.39
Ni	mg/kg	4.2	0.8	14.6	2.6
Ag	mg/kg	19.6	1.6	60.0	--
Pb	mg/kg	5746.6	1155.0	16715.9	38051
K	wt. %	0.5	0.02	1.7	--

Elements	Unit	Tailing Samples (n=22)			Mine Waste Sample (n=1)
		Average	Minimum	Maximum	
Se	mg/kg	0.7	0.6	0.8	2.21
Na	mg/kg	0	0.0	0.2	--
Tl	mg/kg	23	3.2	48.4	70.3
Ti	wt. %	19	19	19	--
U	mg/kg	2	1.2	3.6	0.25
V	mg/kg	32	2	101	4
Zn	mg/kg	1641	48	11937	2262

Figure 7 shows the strong correlation between Fe and S demonstrating the importance of the pyrite content. Samples with significant native sulfur would plot to the right of the pyrite line and those with significant jarosite would plot to the left (Table 2). In contrast, the weaker correlation between Zn and S reflects the fact that pyrite presence is the dominant control on S contents.
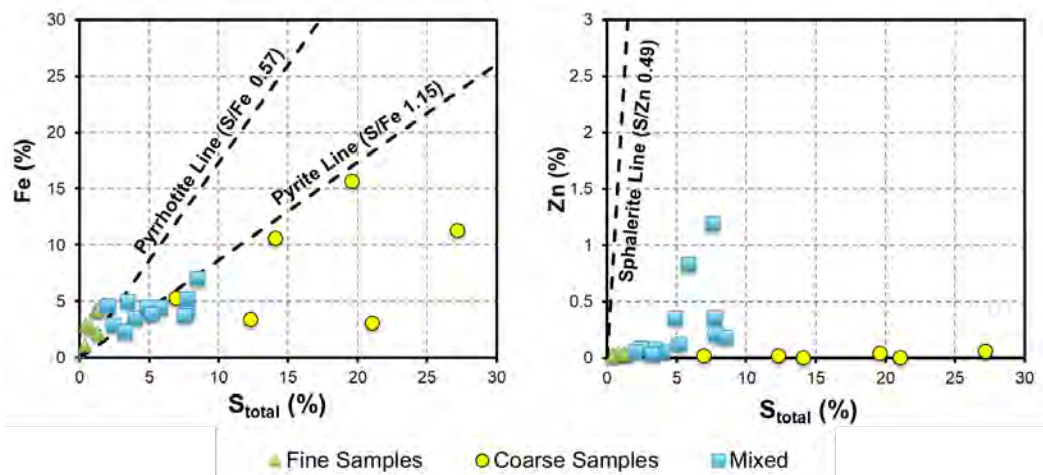
- *Figure 7. Geochemical characteristics of mine waste samples.*

Different efflorescent salts, most notably copiapite [$Fe^{2+}Fe^{3+}_4(SO_4)_6(OH)_2 \cdot 20(H_2O)$], were identified in the surface of the mine waste piles; these salts dissolve easily in water, producing acidic, metal-rich solutions (Table 2; Hammarstrom et al., 2005). This region has strong seasonal variations in precipitation (rainy season from December to March), so higher concentrations of metals are expected to be mobilized into the Crucero River in the rainy season, which increases risks of impacts on Lake Titicaca. The secondary minerals, which are found in the waste mineral assemblages, can also play a crucial role in controlling the mobility of these elements. The Fe and Al oxyhydroxides, some of which are represented by the amorphous phases in Table 2, can sorb these trace elements, which limit their mobility as dissolved constituents, but may enhance their mobility as colloidal particulates in high-energy streams and rivers.

3.1.4. Leaching tests
SPLP leachate results from mine waste samples showed high leachability for As (up to 0.95 mg/L), Cu (up to 57.34 mg/L), Cd (up to 1.13 mg/L), Fe (up to 785.01 mg/L), Zn (up to 91.10 mg/L), Mn (up to 279.14 mg/L), and acidic pH (2.5 to 6.0), which is consistent with the elevated concentrations of these elements in the waste material. Mine waste has elevated concentrations of As (43.5 to 883 mg/kg), Cu (7.9 to 20,106 mg/kg), Pb (1,155 to 16,716 mg/kg), and Zn (48.5 to 11,937 mg/kg) (Table 3).

3.2. Water samples
Water chemistry data and SPLP leachates are shown in Figure 8. Mine portal drainage and leachates from mine waste (tailings and waste rock) contribute significant concentrations of Cd, Fe, Mn, and Zn, among other trace elements to the Cecilia River.
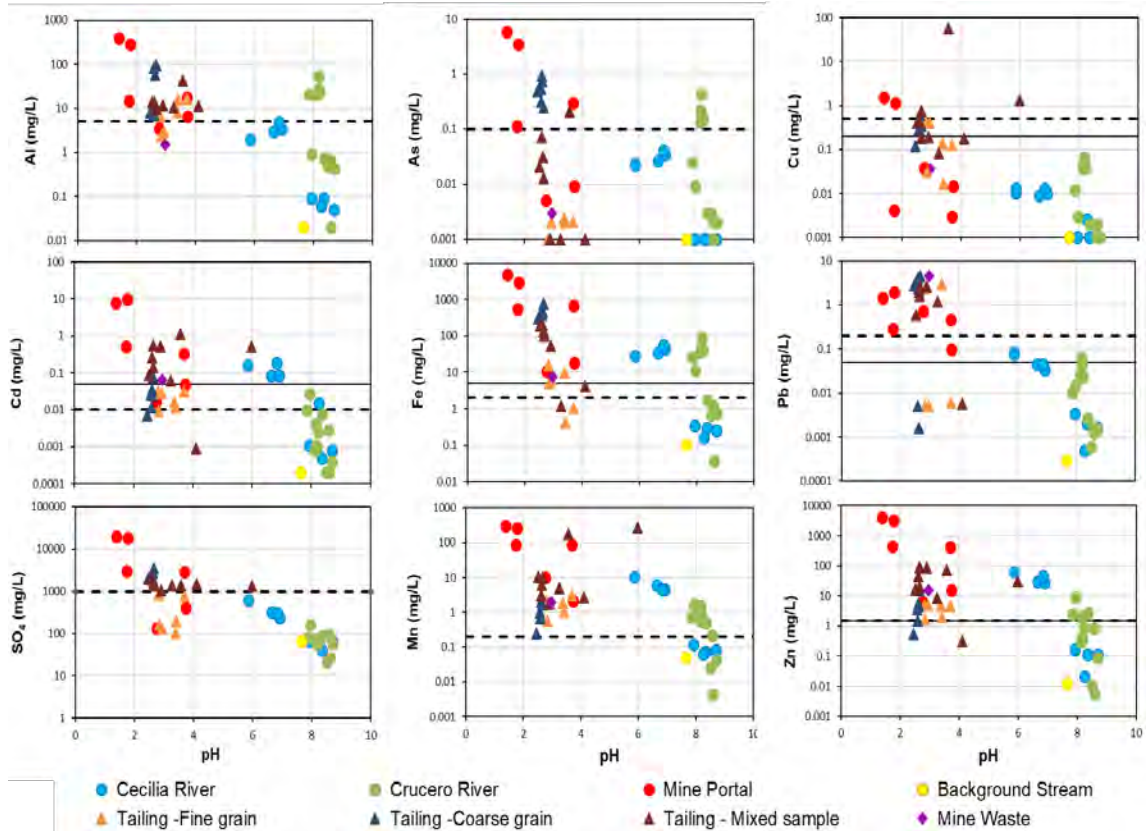
Figure 8. pH vs element concentration for water quality and leachate results (Al, As, Cu, Cd, Fe, Pb, SO₄, Mn, and Zn). *The horizontal solid lines on the graphs represent the Peruvian regulatory standard for mining effluents, and the dashed lines represent the Peruvian environmental regulatory standard for rivers. The tailings and mine waste data are for SPLP leachates.*

4.0.   DISCUSSION

4.1.   Water quality impacts

The pH of the Cecilia River upstream of the Cecilia mine was 8.3, and this value decreased after contact with effluents from mine portals, reaching the value of 5.9 in the last point sampled just before its confluence with the Crucero River (Figure 2). Metal concentrations in the Cecilia River increased by up to two orders of magnitude due to inputs of mine portal drainage and leachates from mine waste piles, which resulted in exceedances of water guidelines for Cd, Fe, Mn, and Zn (Figure 8).

The Crucero River pH values were between 8.0 and 8.7 upstream of its confluence with the Cecilia River. The pH was 8.2 before receiving the inflow from the Cecilia River, but after the confluence the pH dropped to 7.8. It rebounded above 8 less than 5 km downstream of the confluence. The downstream recovery of pH presumably reflects the complete mixing of alkaline water (range: 55–152 mg/L CaCO₃) in the Crucero River with some additional dilution by small tributaries entering the Crucero downstream of its confluence with the Cecilia River.

Figure 9 shows that the Cecilia River inflow increases metal concentrations in the Crucero River after their confluence. The concentrations of these elements in the Crucero River continue to steadily decrease downstream, suggesting that the Cecilia River was the main source of these elements in this reach of the watershed.
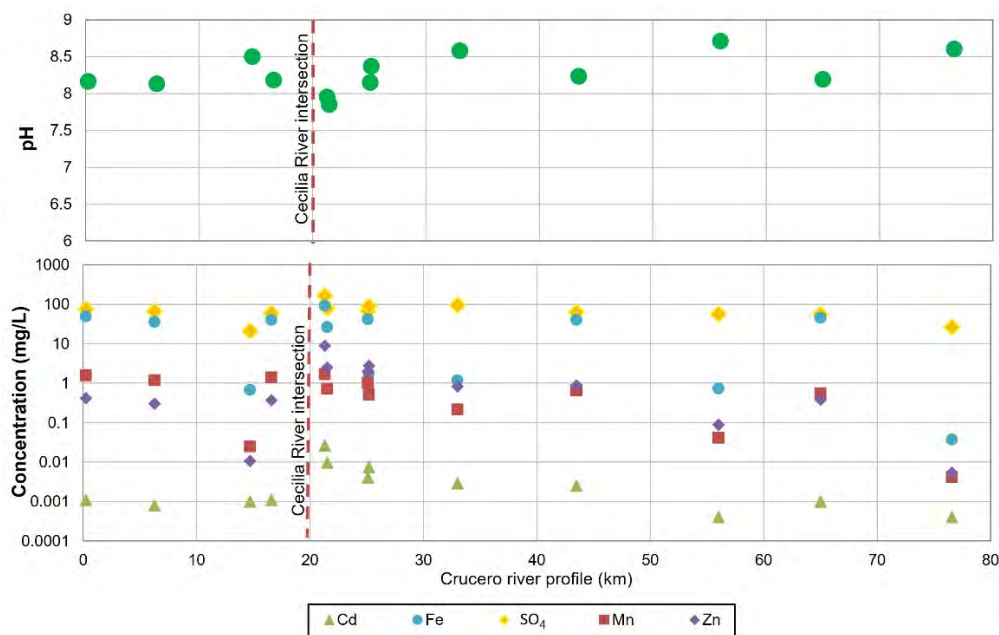
Figure 9. Profiles of stream water total concentrations in Crucero River passing the confluence with the Cecilia River.

Figure 10 shows the ratio of dissolved metal/total metal vs pH, to evaluate the predominant form of metals in the samples. Mine portal samples had the highest proportion of dissolved metals due to their low pH. The ratios of dissolved/total Fe and Cu generally decrease in the Cecilia River as the pH rises. The ratios decrease even more in the Crucero River. The trends in the proportions of dissolved Cu and Zn downstream reflect the pH-dependence of Cu and Zn sorption onto Fe hydroxides, where Cu sorbs at lower pH than Zn.
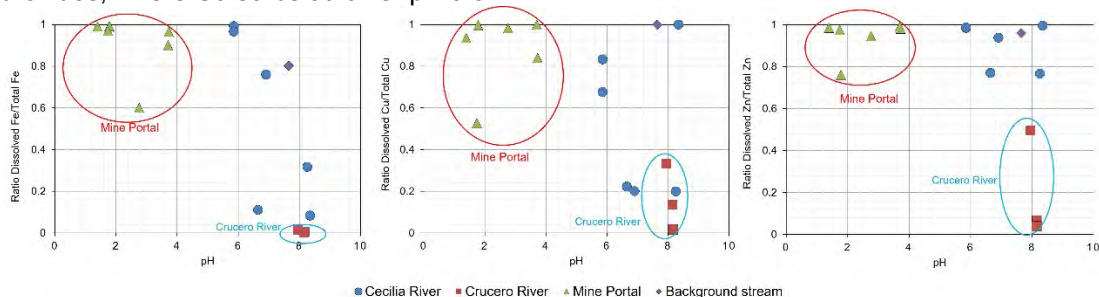

Figure 10. Ratio of total metal/dissolved metal for Fe, Cu, and Zn in the water samples vs pH.

5.0.   CONCLUSIONS AND IMPLICATIONS

This investigation described the geochemical characteristics of the solid waste material and mine water at the abandoned Cecilia mine in the Altiplano of Peru. The results show that the surface water is being impacted by the tailings and mine portal drainage, causing acidic pH (2.5-4.1) and high concentrations of metals such as Al (0.01-98.22 mg/L), Cd (0.001–1.13 mg/L), Fe (0.42-785 mg/L), Mn (0.01-195 mg/L), Pb (0.01-4.45 mg/L), and Zn (0.01-91 mg/L). Groundwater is being impacted by underground workings as evidenced by contaminated waters flowing from mine portals with acidic waters (pH 1.4-3.7). Although the reddish color of the river disappeared 5 km downstream of the Cecilia mine, the concentrations of potentially toxic elements persist even after the pH has been neutralized, resulting in continued loading of metals to the Crucero River. Metal concentrations exceed the water environmental standards for Cd, Fe, Mn and Zn in the Crucero River downstream of its confluence with the Cecilia River.

The climate conditions of the Puno region likely exert a significant influence on the geochemistry of acid mine drainage causing strong annual variation of pH, conductivity, and metals concentration. In the dry season (April to November), the main discharge from the mine site is from the mine portals.

In the rainy season (December to March), the infiltration of rain is expected to dissolve efflorescent salts, thereby increasing loads of acidity and trace elements to the Cecilia and Crucero rivers, which will increase risks to Lake Titicaca.

The results of this study provide insights into remediation strategies for the Cecilia Mine. The generation of metal-rich acid mine drainage from mine waste piles can be addressed by regrading and capping the piles to stop the infiltration of water into the piles. Source control to address the impaired effluent from mine portals is not feasible. Instead, mine portal drainage will likely require passive treatment to improve water quality.

6.0.   REFERENCES

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